PB-230 682

EXPERIMENTAL TREATMENT OF LAKE ERIE WATER, ERIE, PENNSYLVANIA, WATER PLANT

Kenneth A. Dostal, et al

Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

March 1966

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PB 230 682

PROJECT REPORT

EXPERIMENTAL TREATMENT OF LAKE ERIE WATER

ERIE, PENNSYLVANIA, WATER PLANT

by

Kenneth A. Dostal and Gordon G. Robeck

Engineering Activities
Basic and Applied Sciences Program
Federal Water Pollution Control Administration
Cincinnati Water Research Laboratory

March 1966

U.S. Department of Health, Education, and Welfare
Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. Department of Commerce
Springfield VA 22151

85

LIST OF TABLES

Table		Page
1.	Raw water characteristics	8
2.	Characteristics of media used in experimental filters	17
3.	Summary of filter runs	20
4.	Incremental head losses for run 5	37
5.	Summary of algae data	68
6.	Influence of filtration rate on water production	69
7.	Influence of filter media on water production	70
8.	Influence of alum dose on water production	71
9.	Unit water production for runs 5-8 of spring series	72
10.	Expected length of run for various assumed production values	73

LIST OF FIGURES

Figure		Page
1.	Frequency distribution of raw water turbidity values, May 5, 1964 to May 5, 1965.	3
2.	Frequency distribution of coliform organisms in raw water, May 5, 1964 to May 5, 1965.	4
3.	Frequency distribution of plankton in raw water, Jan. 19, 1965 to May 8, 1965.	6
4.	Frequency distribution of plankton in raw water at Buffalo, N.Y., October 1960 to Aug. 1965.	7
5.	Frequency distribution of daily averages of raw water turbidity during test periods.	10
6.	Frequency distribution of plankton in raw water during test periods.	11
7.	Details of dual-media filter head loss taps.	13
8.	Size distribution of sand used in dual-media filter.	15
9.	Size distribution of coal used for dual-media filter.	16
10.	Head loss and turbidity values for run 1 of summer series, Aug. 13, 1964.	19
11.	Head loss and turbidity values for run 2 of summer series, Aug. 17, 1964.	24
12.	Head loss and turbidity values for run 3 of summer series, Aug. 22, 1964.	25
13.	Head loss and turbidity values for run 4 of summer series, Aug. 24, 1964.	27
14.	Head loss and turbidity values for run 5 of summer series, Aug. 25, 1964.	28
15.	Head loss and turbidity values for run 6 of summer series, Aug. 26, 1964.	29
16.	Head loss and turbidity values for run 7 of summer series, Aug. 27, 1964.	30
17.	Head loss and turbidity values for run 1 of fall series, Nov. 18, 1964.	33
18.	Head loss and turbidity values for run 2 of fall series, Nov. 19, 1964.	35
19.	Head loss and turbidity values for run 3 of fall series, Nov. 20, 1964.	36

LIST OF FIGURES (Contd.)

Figure		Page
20.	Head loss and turbidity values for run 4 of fall series, Nov. 21, 1964.	38
21.	Head loss and turbidity values for run 5 of fall series, Nov. 22, 1964.	39
22.	Head loss and turbidity values for run 6 of fall series, Nov. 23, 1964.	41
23.	Head loss and turbidity values for run 7 of fall series, Nov. 24, 1964.	43
24.	Head loss and turbidity values for run 8 of fall series, Nov. 25, 1964.	44
25.	Head loss and turbidity values for run 9 of fall series, Nov. 26, 1964.	46
26.	Head loss and turbidity values for run 10 of fall series, Nov. 26, 1964.	47
27.	Head loss and turbidity values for run 1 of winter series, Feb. 11, 1965.	49
28.	Head loss and turbidity values for run 2 of winter series, Feb. 12, 1965.	51
29.	Head loss and turbidity values for run 3 of winter series, Feb. 13, 1965.	52
30.	Head loss and turbidity values for run 4 of winter series, Feb. 14, 1965.	54
31.	Head loss and turbidity values for run 5 of winter series, Feb. 15, 1965.	55
32.	Head loss and turbidity values for run 6 of winter series, Feb. 16, 1965.	56
33.	Head loss and turbidity values for run 1 of spring series, May 18, 1965.	57
34.	Head loss and turbidity values for run 2 of spring series, May 19, 1965.	58

LIST OF FIGURES (Contd.)

Figure		Page
35.	Head loss and turbidity values for run 3 of spring series, May 20, 1965.	60
36.	Head loss and turbidity values for run 4 of spring series, May 21, 1965.	61
37.	Head loss and turbidity values for run 5 of spring series, May 22, 1965.	62
38.	Head loss and turbidity values for run 6 of spring series, May 23, 1965.	64
39.	Head loss and turbidity values for run 7 of spring series, May 25, 1965.	65
40.	Head loss and turbidity values for run 8 of spring series, May 26, 1965.	67

Project Report

EXPERIMENTAL TREATMENT OF LAKE ERIE WATER

by

Kenneth A. Dostal and Gordon G. Robeck

This study resulted from a discussion with representatives of the Bureau of Water for Erie, Pennsylvania, concerning various possible approaches for expansion of their municipal water plants. Two small experimental filters were installed in one of the water treatment plants by the Public Health Service as part of a continuing study in which various aspects of water treatment are being reviewed. The study was designed to check the influence of high-rate and dual-media filtration coupled with the elimination of conventional flocculators and settling tanks on the finished-water quality.

A series of 61 filter runs was made during the 1-year study at filtration rates varying from 2 to 6 gpm/ft^2. The addition of 5 to 15 mg of alum per liter to the raw water just prior to filtration through dual-media filters resulted in an effluent of very good quality. Both turbidity and algae were consistently reduced to low levels. Length of filter run depended upon the raw water turbidity, alum dose, filtration rate, and size of coal used in the dual-media filters.

Prior to this study, segments of the conventional water treatment process (coagulation, flocculation, sedimentation, and filtration) had been reviewed in three cooperative field studies. The first field study[1], at a 3-mgd water treatment plant in Gaffney,

---

This work was performed while the authors were members of the Division of Water Supply and Pollution Control, Public Health Service, Department of Health, Education, and Welfare.

South Carolina, was designed to determine the effect of shortened flocculation and sedimentation times plus higher filtration rates on the quality of the finished water. A similar study[2] was conducted in a 4-mgd water treatment plant located in Easley, South Carolina. The Easley plant utilized sand as the filter media, and the Gaffney plant utilized anthracite. In the second study several runs were made with a small experimental filter containing a coarse coal layer over a layer of fine sand. The third study[3] involved small experimental filters to check the influence of both high-rate and dual-media filtration on the finished-water quality and was conducted at a water plant that uses a cold lime-soda softening process.

RAW WATER SOURCE AND QUALITY

Lake Erie serves as the raw water source for both of Erie's municipal water plants, the West Plant and the Chestnut Street Plant. Each plant has a separate intake, about a mile offshore and 24 feet below the surface of the water. From May 5, 1964 to May 5, 1965, plant personnel made 259 turbidity measurements on the raw water entering the treatment plant. A frequency distribution of these determinations is shown in Figure 1. Fifty percent of the daily turbidity measurements were 3.5 Jackson units or less, and 90 percent were below 15 J.u. During the same 12-month period 197 measurements were made on the coliform content of the raw water; this information is shown in Figure 2. Fifty percent of the determinations yielded a value of 3.5 coliforms per 100 ml or less, and 90 percent of the reported values were less than 50 per 100 ml. On January 19, 1965,

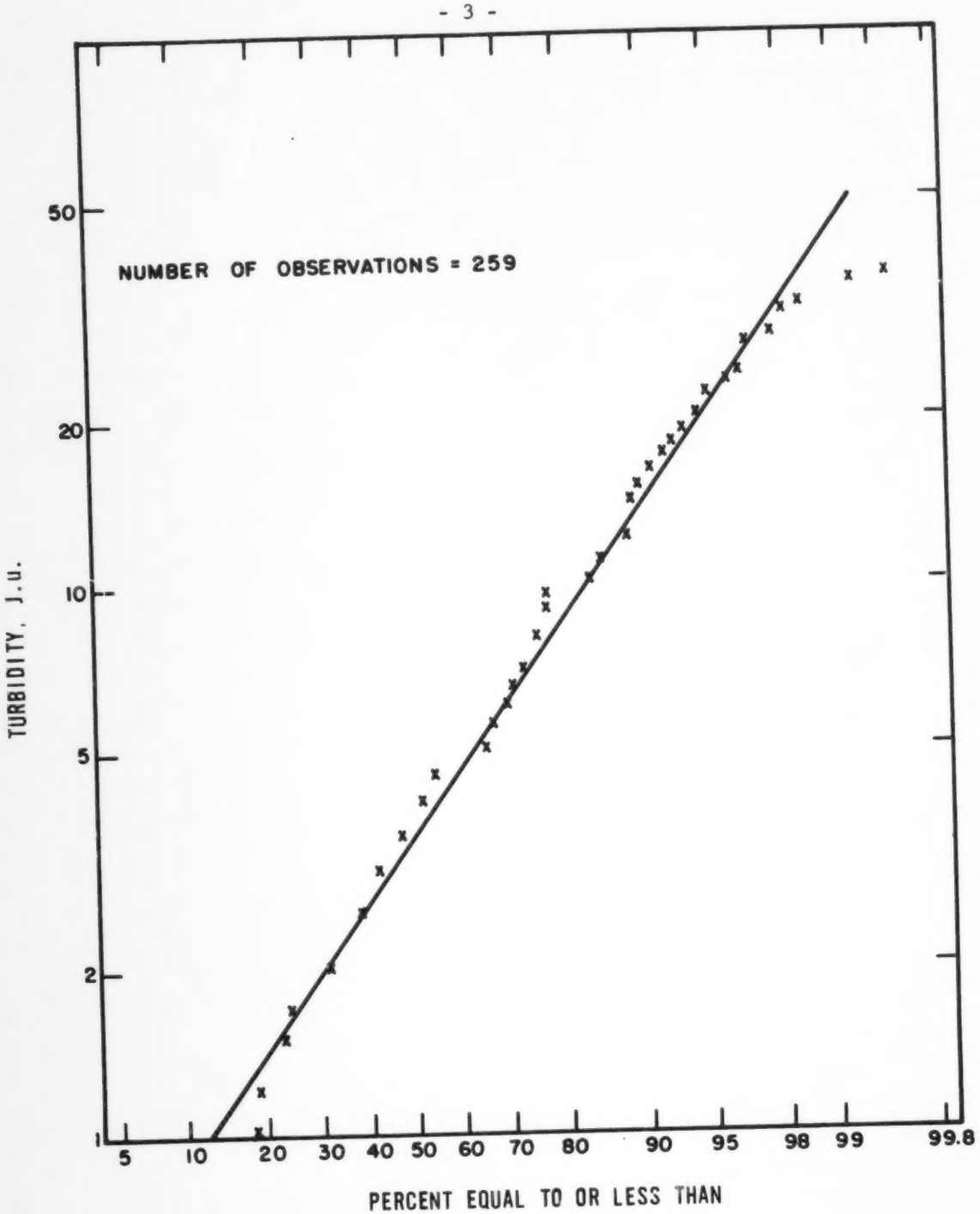

Figure 1. Frequency distribution of raw water turbidity values, May 5, 1964 to May 5, 1965.

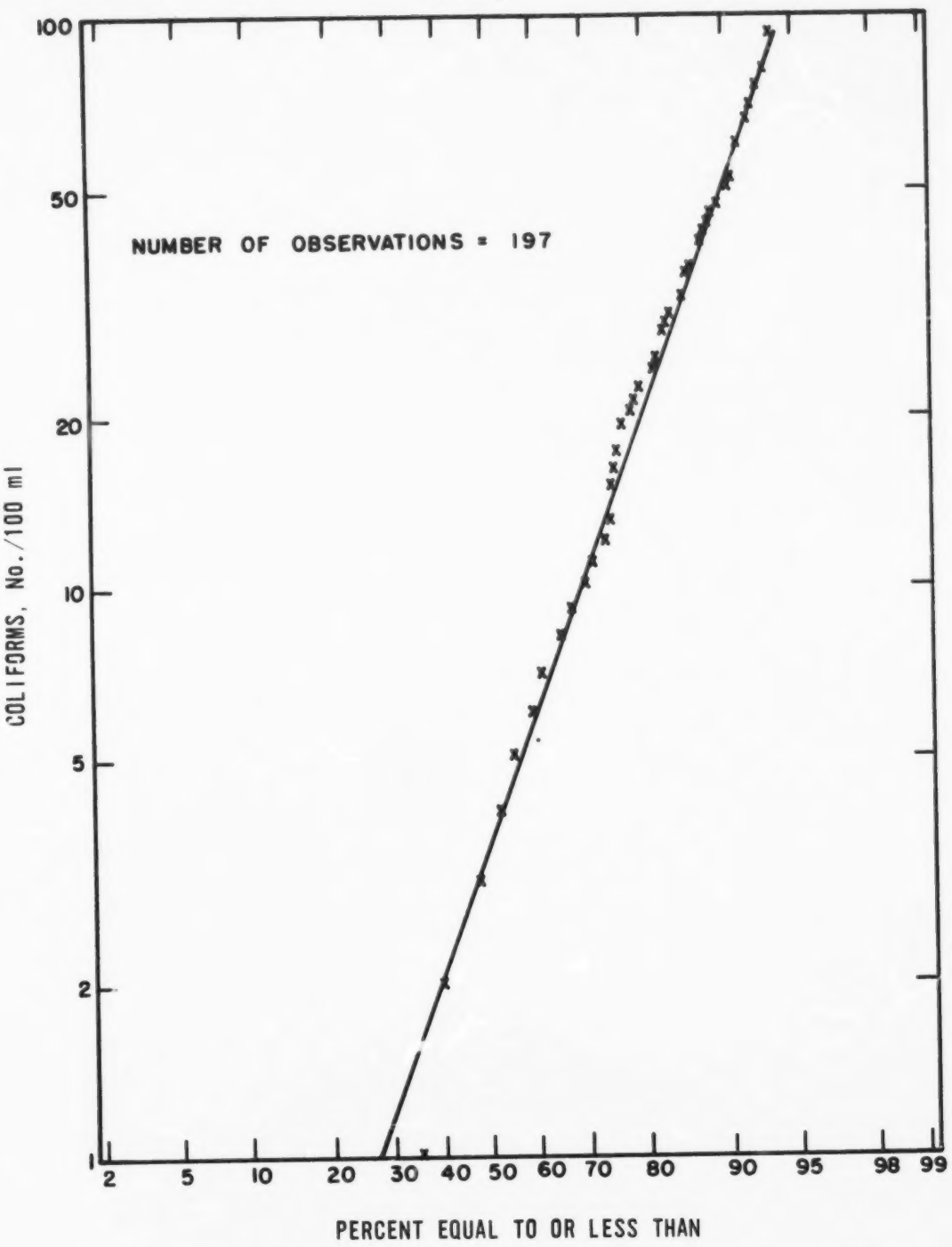

Figure 2. Frequency distribution of coliform organisms in raw water, May 5, 1964 to May 5, 1965.

the water treatment plant personnel started a routine program of algae identification and enumeration. Figure 3 presents a frequency distribution for the 58 measurements made prior to May 8, 1965. Fifty percent were less than 350, and ninety percent of the values were less than 800 per ml.

Inasmuch as the algae data shown in Figure 3 covered only a 4-month period, additional information was desirable. The only other algae data found for Lake Erie were from the Public Health Service Water Pollution Surveillance System, which has a sampling station at the water treatment plant in Buffalo, New York. The Buffalo intake is slightly over a mile from shore in about 12 feet of water. A frequency distribution of 98 counts over nearly a 5-year period is shown in Figure 4. Water characteristics at this plant are very similar to those encountered at the water plants in Erie, Pennsylvania. A comparison of Figures 3 and 4 shows that the algae counts are fairly similar; therefore, the 4-month data (Figure 3) may be reasonably representative of what would be expected throughout a year or longer.

The raw water characteristics, listed in Table 1, for the four periods in which the experimental work was completed indicate the turbidity ranged from 2 to 58 J.u., algae counts ranged from 30 to 960/ml, and the temperature varied from 34 to 69°F.

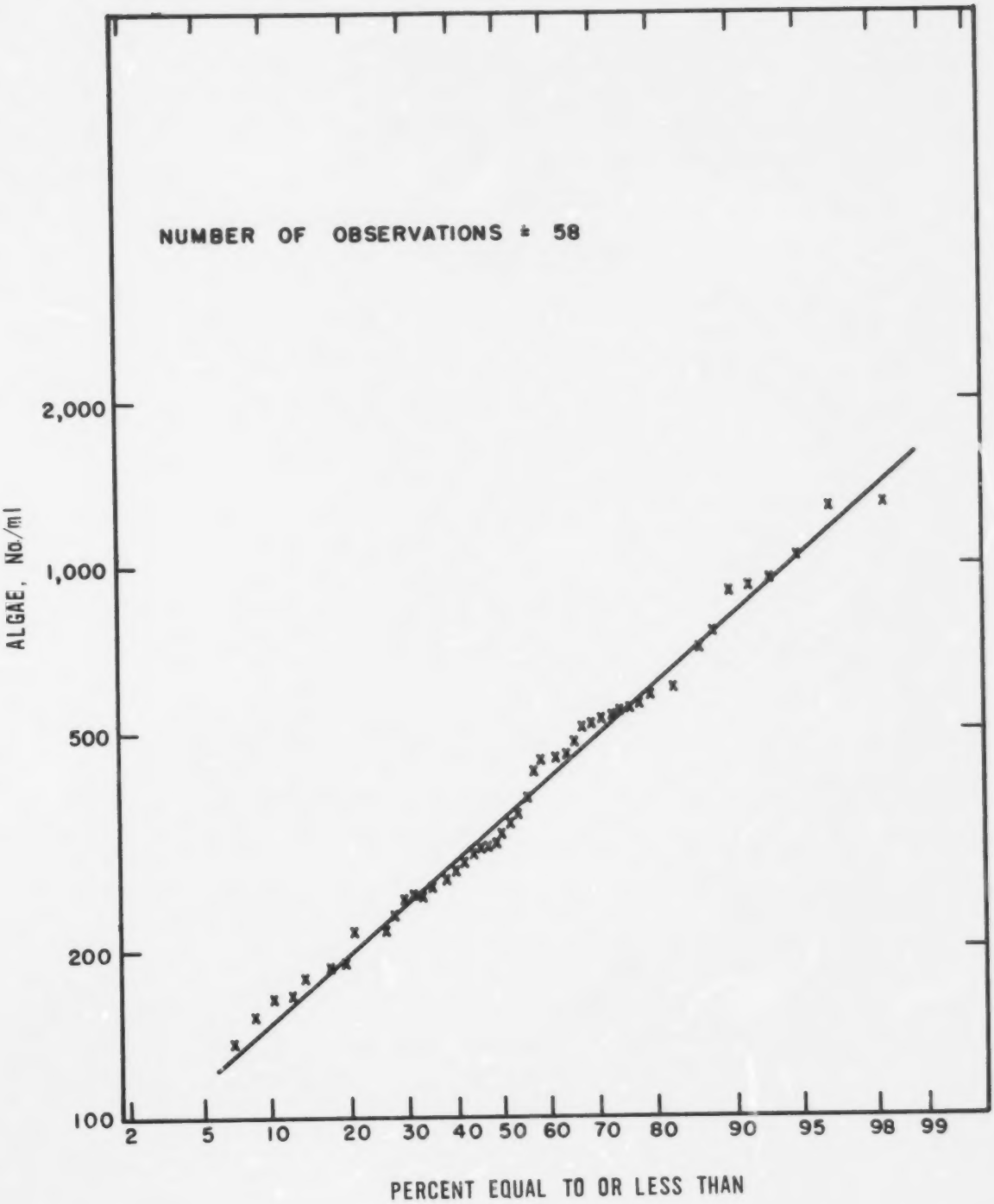

Figure 3. Frequency distribution of algae in raw water, Jan. 19, 1965 to May 8, 1965.

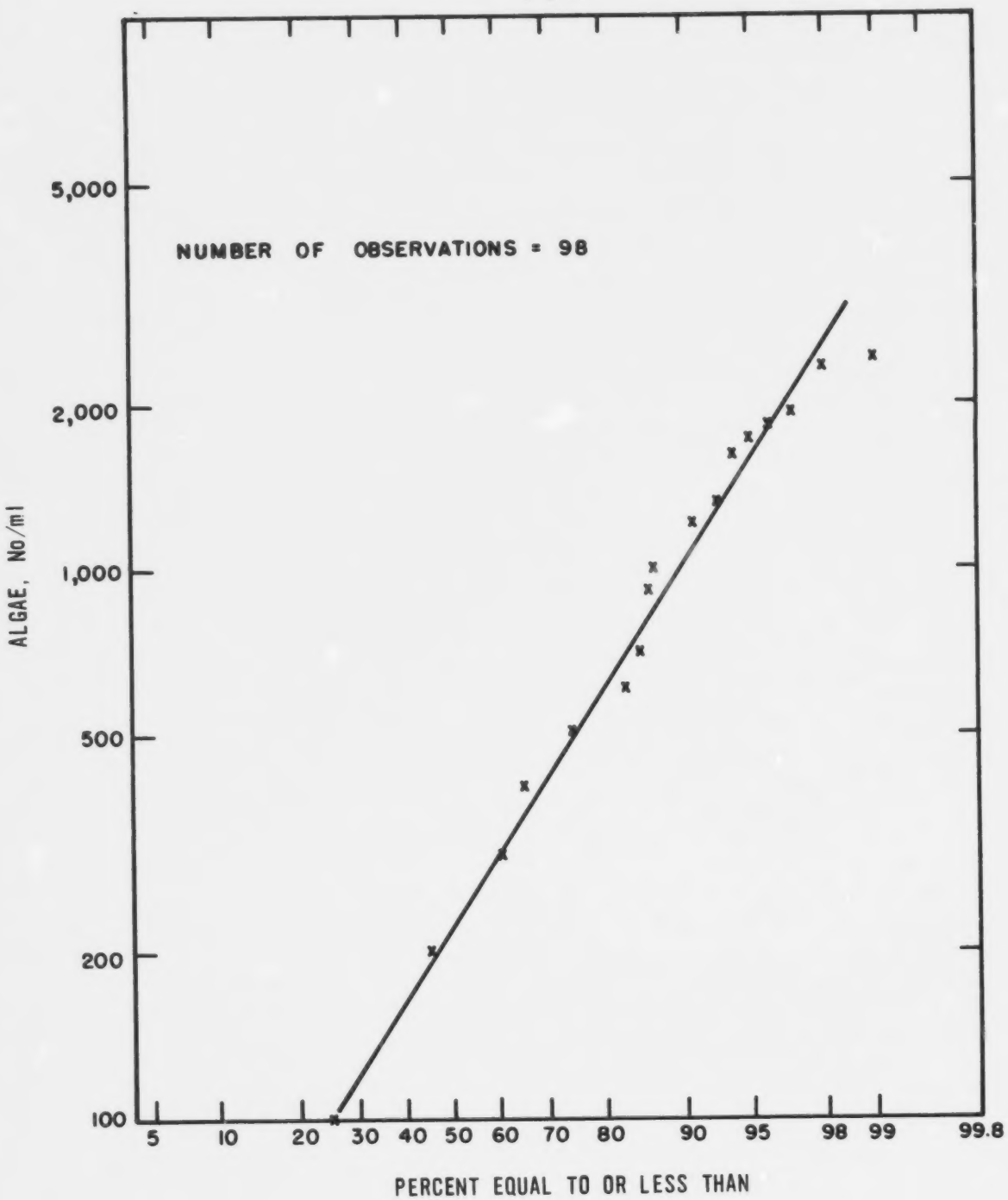

Figure 4. Frequency distribution of algae in raw water at Buffalo, N.Y., Oct., 1960 to Aug., 1965.

Table 1. RAW WATER CHARACTERISTICS

Date		pH	Temp., °F	Hardness (as $CaCO_3$) mg/liter	Alkalinity mg/liter	Turbidity, J.u.	Algae, No./ml
From	To						
8/13/64	8/28/64	7.8-8.0	68-69	128-131	93-98	1-16	430-840
11/18/64	11/27/64	7.4-7.8	47-52	124-135	91-94	5-58	220-960
2/11/65	2/19/65	7.7-8.2	34-41	123-137	86-95	3-18	30-220
5/18/65	5/27/65	7.3-7.8	52-58	130-139	91-95	2-24	80-190

In order to see whether the algae numbers and turbidities encountered during the test periods were representative of those measured by the Erie water plant personnel, frequency distributions were also plotted for the study periods. Figure 5 presents the frequency distribution of the raw water turbidities (daily averages) found during the various filter runs. Based on this information the filtration experiments handled influents slightly higher in turbidity than expected for the 12-month period (Figure 1). Algae counts during the test periods were slightly lower than expected, as shown by the frequency distribution on Figure 6. This was probably due to the facts that the water plant algae data (Figure 3) covered only 4 consecutive months whereas the experiments were conducted during each of the four seasons and that both sets of observations were somewhat limited in number.

DESCRIPTION OF WATER PLANTS

In 1914 the Chestnut Street water treatment plant was completed with a design rate of 24 mgd. Expansion in 1925 increased the capacity to 32 mgd, which sufficied until 1932. At that time West Plant with a design rate of 15 mgd was completed; it was expanded in 1951 to 28 mgd, which gave a total capacity of 60 mgd.

Since only raw water was used at the West Plant, a brief description of this plant will suffice. Raw water is treated with alum prior to passing over weirs into the flocculation basins. Mechanical flocculation of about 30 minutes is provided prior to sedimentation. Design detention time in the sedimentation basins is about 3.5 hours. The filters were designed to operate at a rate of 2 gpm/ft^2. Both pre- and post-chlorination is practiced, and powdered activated carbon is

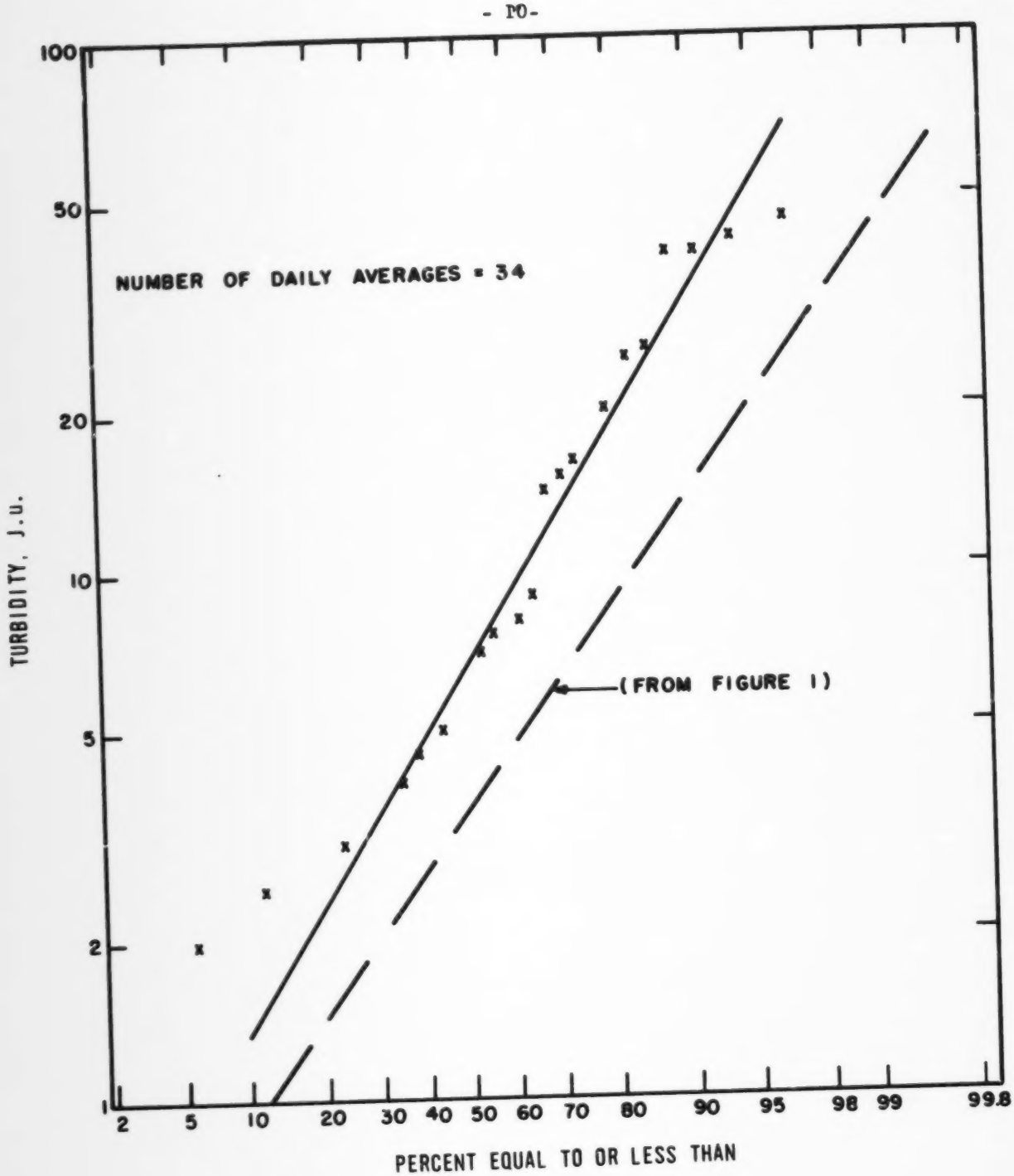

Figure 5. Frequency distribution of daily averages of raw water turbidity during test periods.

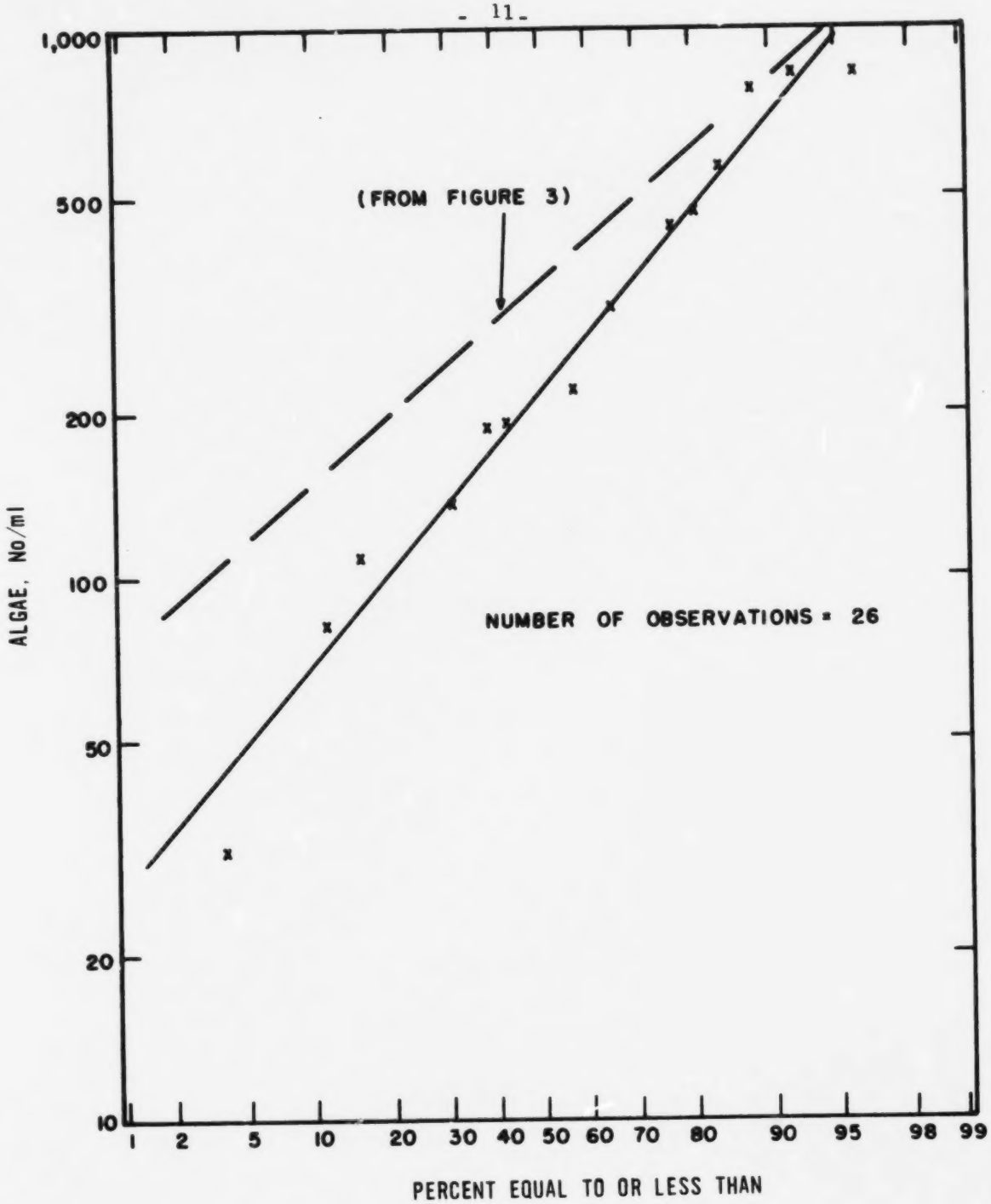

Figure 6. Frequency distribution of algae in raw water during test periods.

added when necessary for control of tastes and odors. When tannins and lignins are encountered in the raw water, potassium permanganate is added. Soda ash is added when necessary to raise pH.

TEST EQUIPMENT AND PROCEDURES

The equipment used in this study consisted of two small experimental filters, pumps for feeding chemicals and controlling the rate of flow, a head loss recorder for continuous measurement of the head loss at four points in each of the filters, and two turbidimeters. One turbidimeter continuously measured and recorded the raw water turbidity, and the other was used to measure and record the effluent turbidities from the two small filters and one of the full-scale filters. Each of the experimental filter containers was constructed of 4-inch-I.D., clear plexiglass. The 24 inches of filter media was supported by a perforated plate and screen. Figure 7 shows the locations of the four points in the filter selected for head loss measurement. Incremental head loss measurements are required with dual-media filters to determine the location of floc deposition.

Throughout this study media sizes were varied in the dual-media filter. About half of the filter runs were conducted with a media combination referred to as "standard." This combination, used often in past experimental work, consists of 18 inches of coal with an effective size (e.s.) of 1.00 mm and a uniformity coefficient (u.c.) of 1.11 over 6 inches of sand (e.s. = 0.49 mm, u.c. = 1.14). Since both media size ranges in the standard were very narrow by design and thus not readily available for full-scale plants, other media sizes were selected from commercially available materials. All filter media other than the standard contained 18 inches of coal over 6 inches of sand

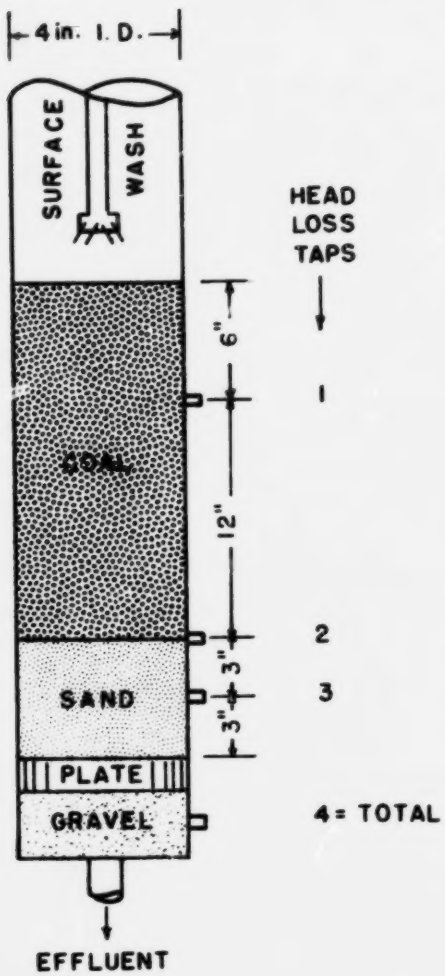

Figure 7. Details of dual-media filter headloss taps.

with an e.s. = 0.43 mm and a u.c. = 1.62 (see Figure 8). At various times the size of the coal was altered. The initial size distribution of the coal is shown in Figure 9 (e.s. = 0.93 mm, u.c. = 1.71). For the filter labeled "1.0", the coal was sieved and everything smaller than 1.0 mm was discarded. In a full-scale filter this would be accomplished by removing the top 13 percent of the coal layer following backwashing. Other filters with the nomenclature of "1.2", "1.4", and "1.7" contained commercially available coal with material smaller than 1.2, 1.4, and 1.7 mm, respectively, removed prior to adding the 18 inches of coal to the filter. With the size of coal purchased, the amounts of coal discarded ranged from 13 percent for the "1.0" filter media to 70 percent for the "1.7" media. Regardless of media size, the same weights of sand and coal were added to every filter. Table 2 lists the effective size and uniformity coefficient for the various coal and sand layers used in the filters.

Prior to starting each filtration run, the experimental filters were backwashed thoroughly to assure cleanliness and the media was then packed to a predetermined level. In addition to the continuous measurement of incremental head losses and influent and effluent turbidities, grab samples were taken for temperature, pH, alkalinity, and total algae determinations. Each run was continued until one or both of the filters had a turbidity breakthrough or the total head loss exceeded 7 feet.

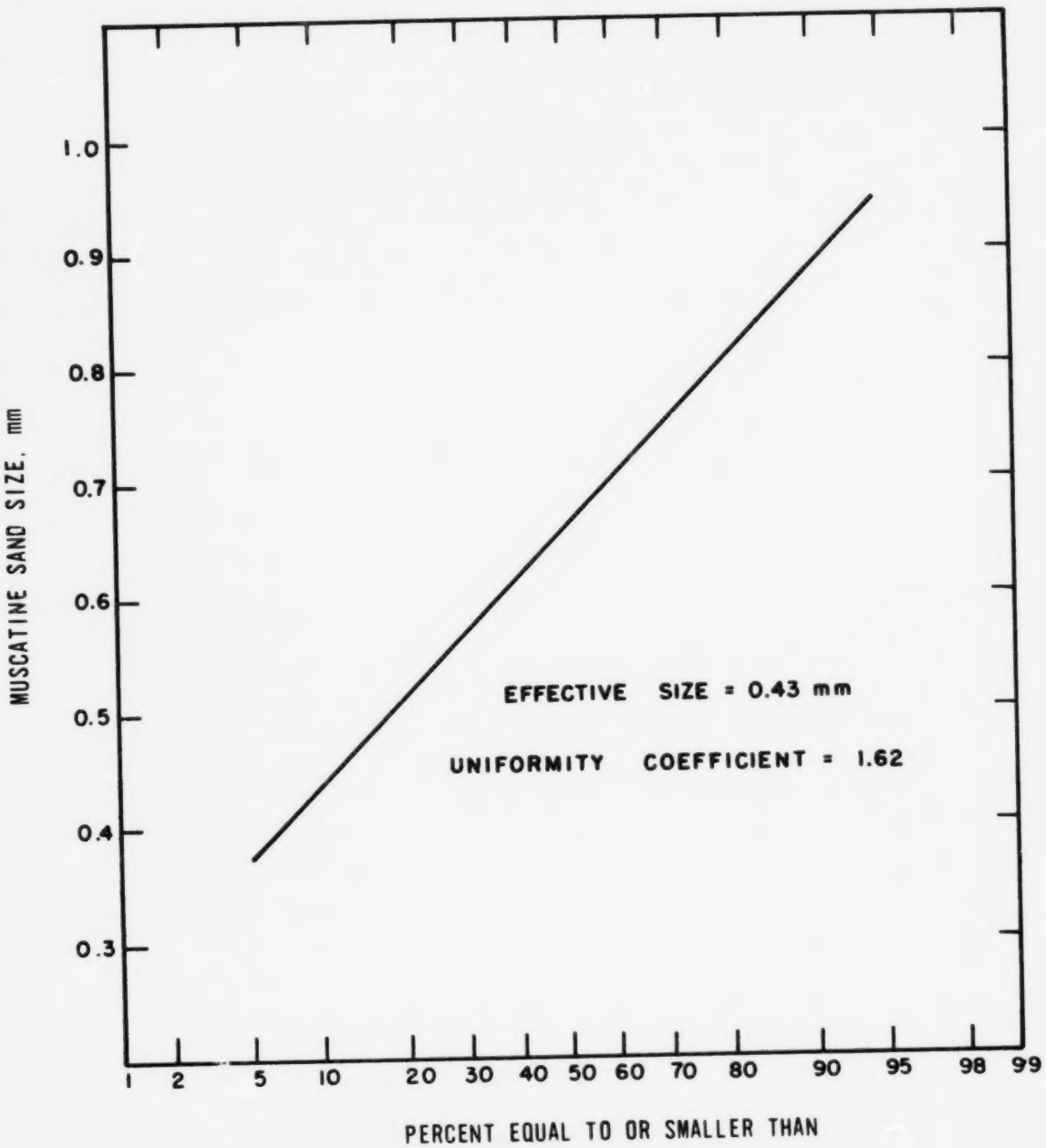

Figure 8. Size distribution of sand used in dual-media filter.

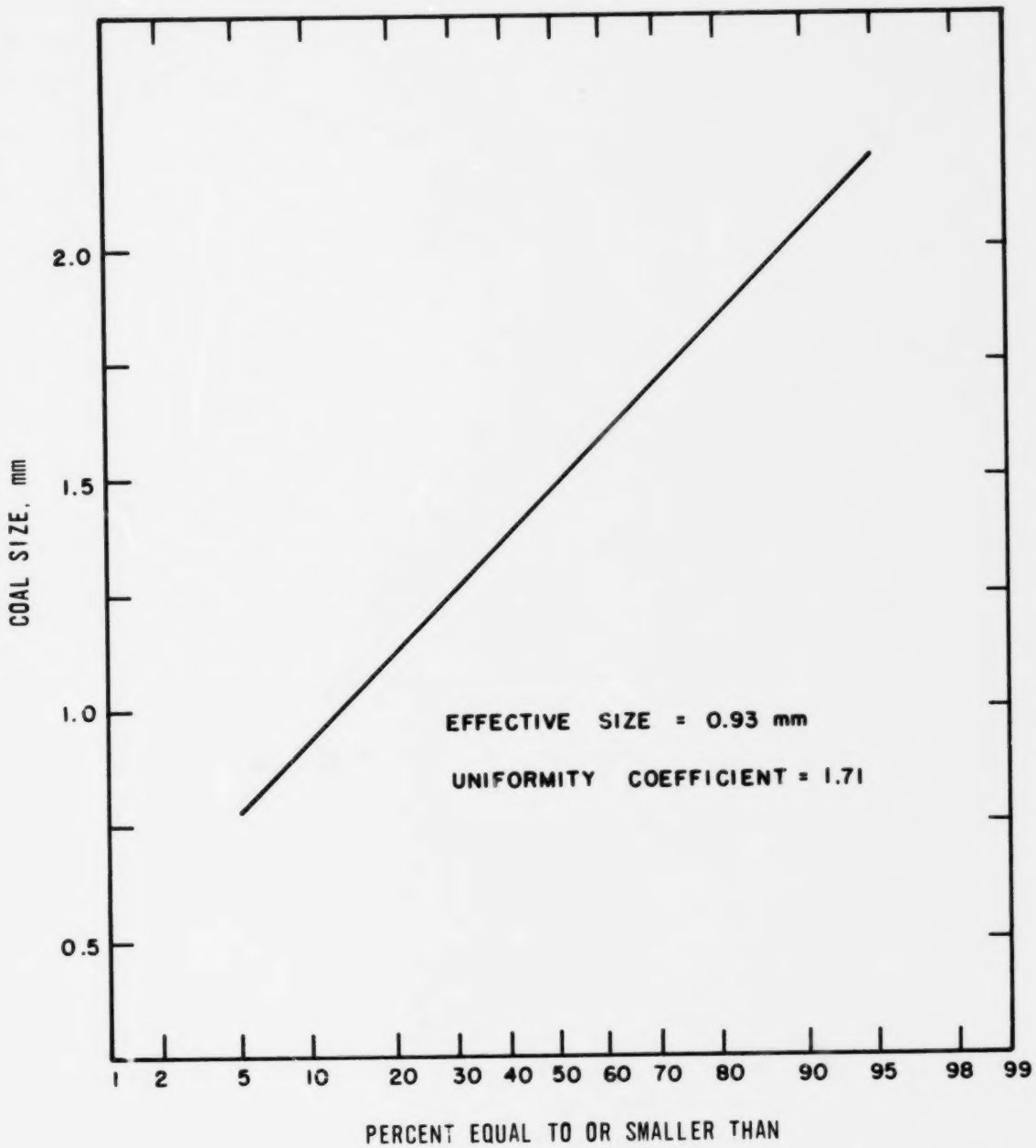
COAL SIZE, mm
2.0
1.5
1.0
0.5
EFFECTIVE SIZE = 0.93 mm
UNIFORMITY COEFFICIENT = 1.71
1 2 5 10 20 30 40 50 60 70 80 90 95 98 99
PERCENT EQUAL TO OR SMALLER THAN

Figure 9. Initial size distribution of coal used for dual-media filter.

Table 2. CHARACTERISTICS OF MEDIAS USED IN EXPERIMENTAL FILTERS

Nomenclature	Media type	Depth,[a] inches	Effective size, mm	Uniformity coefficient
Standard	Coal	18	1.00	1.11
	Sand	6	0.49	1.14
1.0	Coal	18	1.14	1.45
	Sand	6	0.43	1.62
1.2	Coal	18	1.29	1.33
	Sand	6	0.43	1.62
1.4	Coal	18	1.46	1.23
	Sand	6	0.43	1.62
1.7	Coal	18	1.72	1.15
	Sand	6	0.43	1.62

a - Similar weights added in each case: coal, 1,960 grams based on specific gravity = 2.65 and 40 percent porosity; and sand, 2,880 grams based on specific gravity = 1.55 and 50 percent porosity.

RESULTS

Turbidity

Summer Series - Table 3 contains a summary of the results from 61 filter runs made during four seasons in 1964 and 1965. In all of the runs, alum was added to the raw water entering the top of the filter. The first series or "summer series" of seven runs, conducted from August 13-27, 1964, was designed to check the influence of filtration rate on both the length of run and the effluent quality using the "standard" filter.

Filter influent and effluent turbidities along with the incremental head losses for the seven runs are presented in Figures 10 through 16. In the first run, shown in Figure 10, both filters were fed 20 mg of alum per liter and were operated at filtration rates of 4 and 6 gpm/ft^2. During this run, the influent turbidity averaged 16 J.u. and the effluent turbidities were consistently below 0.1 J.u. Because of the high alum dose and poor head-loss distribution, the run lengths were very short, 6 hours at the 4 gpm/ft^2 filtration rate and only 2 hours at the higher rate. As seen by the head-loss curves for both filters, most of the removal took place in the top 6 inches of the filter. Filter 2 at 6 gpm/ft^2 did not result in any appreciable improvement in floc distribution over filter 1 at 4 gpm/ft^2. As shown later in this study by runs with similar influent turbidity levels, 20 mg/liter was probably an excessive amount.

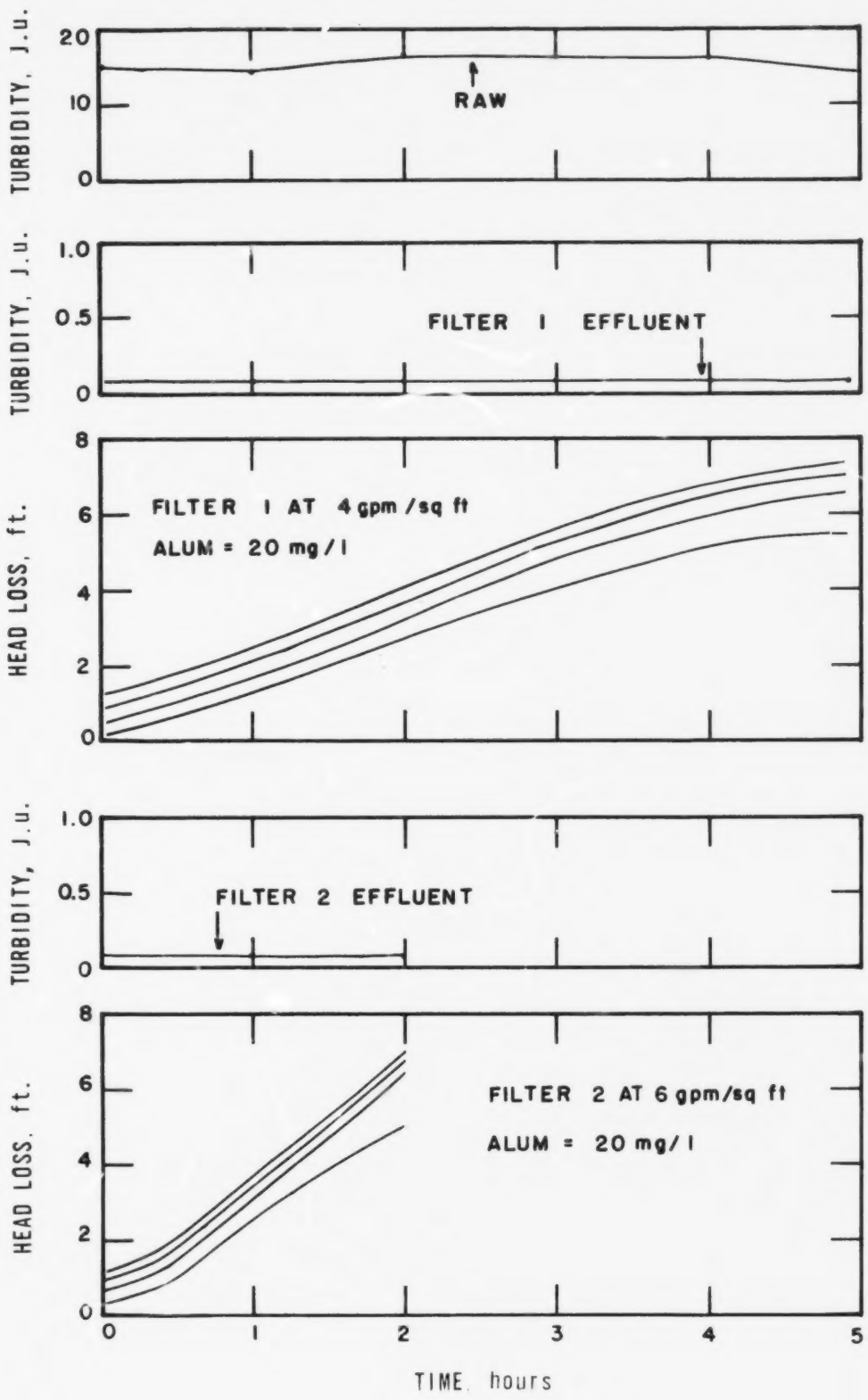

Figure 10. Head loss and turbidity values for run 1 of summer series. Aug. 13, 1964.

TABLE 3. SUMMARY OF FILTER RUNS

Run No.	Filter No.	Filter Media	Rate, gpm/ft^2	Alum Dose mg/liter	Raw Turbidity, J.u.	Filter Effluent Turbidity, J.u.	Final Head loss, ft	Length of run, hr.
					Summer Series			
1	1	Std.[a]	4	20	16	0.1	7.4	4.9
	2	Std.	6	20	15	0.1	7.0	2.0
2	1	Std.	4	10	3	0.1	7.8	9.0
	2	Std.	6	10	3	0.1	7.8	9.0
3	1	Std.	2	10	3	0.1	7.6	29.5
	2	Std.	4	10	3	0.1	7.8	9.0
4	1	Std.	6	10	4	0.1	7.0	6.0
	2	Std.	2	10	4	0.1	5.4	17.0
5	1	Std.	6	10	3	0.1	7.6	6.0
	2	Std.	2	10	4	0.1	7.5	19.0
6	1	Std.	4	10	3	0.1	7.8	8.5
	2	Std.	2	10	3	0.1	7.6	23.0
7	1	Std.	4	10	2	0.1	7.6	9.0
	2	Std.	4	5	2	0.1	4.0	21.5
					Fall Series			
1	1	1.0[b]	4	10	25	0.1	7.4	8.5
2	1	1.0	4	10	8	0.1	7.6	13.0
	2	Std.	4	10	7	0.1	6.8	9.0
3	1	1.2[c]	4	10	28	0.1	7.4	9.0
	2	Std.	4	10	24	0.1	8.0	6.4
4	1	1.2	6	5	> 35	0.8	7.2	8.0
	2	Std.	6	5	> 35	0.2	7.2	6.0
5	1	1.2	6	10	> 35	0.1	7.2	5.0
	2	Std.	6	10	> 35	0.1	7.2	3.0

TABLE 3. SUMMARY OF FILTER RUNS (Contd.)

Run No.	Filter No.	Filter Media	Rate gpm/ft^2	Alum Dose mg/liter	Raw Turbidity J.u.	Filter Effluent Turbidity, J.u.	Final Head loss, ft	Length of run, hr.
6	1	1.4[d]	2	10	> 35	0.1	7.2	22.0
	2	Std.	2	10	> 35	0.2	7.0	13.0
7	1	1.4	6	10	22	0.1	7.3	6.4
	2	Std.	6	10	20	0.1	7.9	5.0
8	1	1.7[e]	2	10	13	0.3	3.0	20.0
	2	Std.	2	10	13	0.1	7.6	20.0
9	1	1.7	6	10	> 35	0.1	7.2	6.5
	2	Std.	6	10	> 35	0.1	7.2	5.0
10	1	1.7	4	10	> 35	0.1	7.3	13.5
	2	Std.	4	10	> 35	0.1	7.0	8.0
					Winter Series			
1	1	Std.	2	10	4	0.1	7.0	19.5
	2	1.0	2	10	4	0.1	3.8	20.0
2	1	Std.	6	10	4	0.1	7.0	3.1
	2	1.0	6	10	4	0.2	7.0	4.9
3	1	Std.	4	10	9	0.1	7.1	7.5
	2	1.0	4	10	9	0.2	6.8	9.5
4	1	Std.	2	10	8	0.2	7.0	21.0
	2	1.4	2	10	8	0.2	4.8	24.0
5	1	Std.	4	10	7	0.1	6.7	5.6
	2	1.4	4	10	7	0.2	7.0	10.0
6	1	Std.	6	10	8	0.1	7.0	3.6
	2	1.4	6	10	8	0.3	7.0	7.2
					Spring Series			
1	1	1.0	3	10	5	0.1	6.9	18.5
	2	1.0	3	5	5	1.0	2.8	24.5
2	1	1.0	5	10	20	0.4	7.1	6.8
	2	1.0	5	5	20	4.0	2.8	7.0
3	1	1.0	3	7.5	7	0.4	7.0	24.0
	2	1.0	3	12.5	7	0.2	7.0	18.0
4	1	1.0	5	7.5	7	0.5	6.8	9.6
	2	1.0	5	12.5	7	0.2	7.0	6.8

TABLE 3. SUMMARY OF FILTER RUNS (Contd.)

Run No.	Filter No.	Filter Media	Rate gpm/ft^2	Alum Dose mg/liter	Raw Turbidity J.u.	Filter Effluent Turbidity, J.u.	Final Head loss, ft	Length of run, hr.
5	1	1.0	5	12.5	5	0.1	7.2	6.0
	2	1.4	5	12.5	5	0.2	7.2	9.6
6	1	1.0	3	7.5	3	0.3	7.3	25.6
	2	1.4	3	7.5	3	0.3	7.0	38.0
7	1	1.0	5	7.5	2	0.2	7.0	9.3
	2	1.4	5	7.5	2	0.2	7.0	14.1
8	1	1.0	3	12.5	3	0.1	7.0	16.0
	2	1.4	3	12.5	3	0.1	6.1	20.0

---

a - Std. = 18 inches of coal (e.s. = 1.00 mm, u.c. = 1.11) over 6 inches of sand (e.s. = 0.49 mm, u.c. = 1.14).

b - 1.0 = 18 inches of coal (originally: e.s. = 0.93 mm, u.c. = 1.71) after all particles less than 1.0 mm removed, over 6 inches of sand (e.s. = 0.43 mm, u.c. = 1.62).

c - 1.2 - same as b except particles less than 1.2 mm removed.

d - 1.4 - same as b except particles less than 1.4 mm removed.

e - 1.7 - same as b except particles less than 1.7 mm removed.

In the second run, shown in Figure 11, the raw water turbidity dropped to 3 J.u. and the alum dose was reduced to 10 mg/liter while the filtration rates were held at 4 and 6 gpm/ft^2. Both filters again produced an effluent with a turbidity less than 0.1 J.u., but there was an improvement in the length of run. The importance of floc distribution throughout the bed depth is shown by this run. For example, the top 6 inches of coal in filter 1 had a head loss of 5.7 feet upon termination of the run, whereas the top 6 inches of filter 2 had a head loss of 4.0 feet. Both filters had the same total head loss after 9 hours, thus filter 2 operating at a 6-gpm/ft^2 rate produced 50 percent more water than filter 1.

In run 3 (Figure 12) the filtration rates were changed to 2 and 4 gpm/ft^2 and the alum dose was held at 10 mg/liter. Both effluent turbidities were consistently below 0.1 J.u. with a run length for filter 1 at 2 gpm/ft^2 of 29.5 hours and for filter 2 of 9 hours. One of the reasons for filter 1 lasting more than twice as long as filter 2 was probably due to the lower raw water turbidity during the 12- to 24-hour period.

A very poor effluent was produced during the first 3 hours of run 4 by filter 1, but this was a result of a breakdown in the alum feed. Filter 2 produced an effluent with a turbidity less than 0.1 J.u. and reached a total head loss of 5.3 feet in 17 hours, with nearly all of the removal occurring in the top 6 inches of the coal.

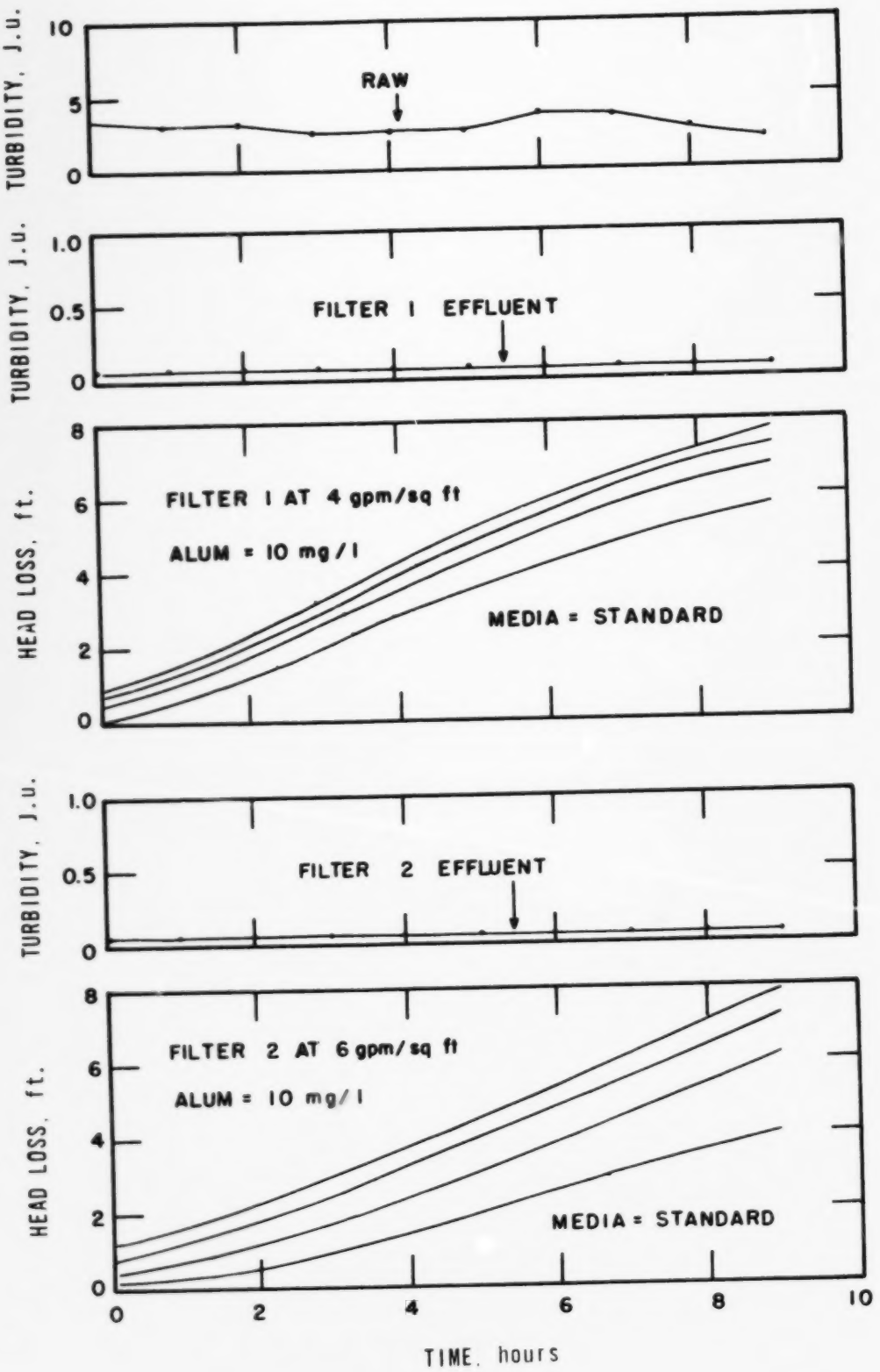

Figure 11. Head loss and turbidity values for run 2 of summer series. Aug. 17, 1964.

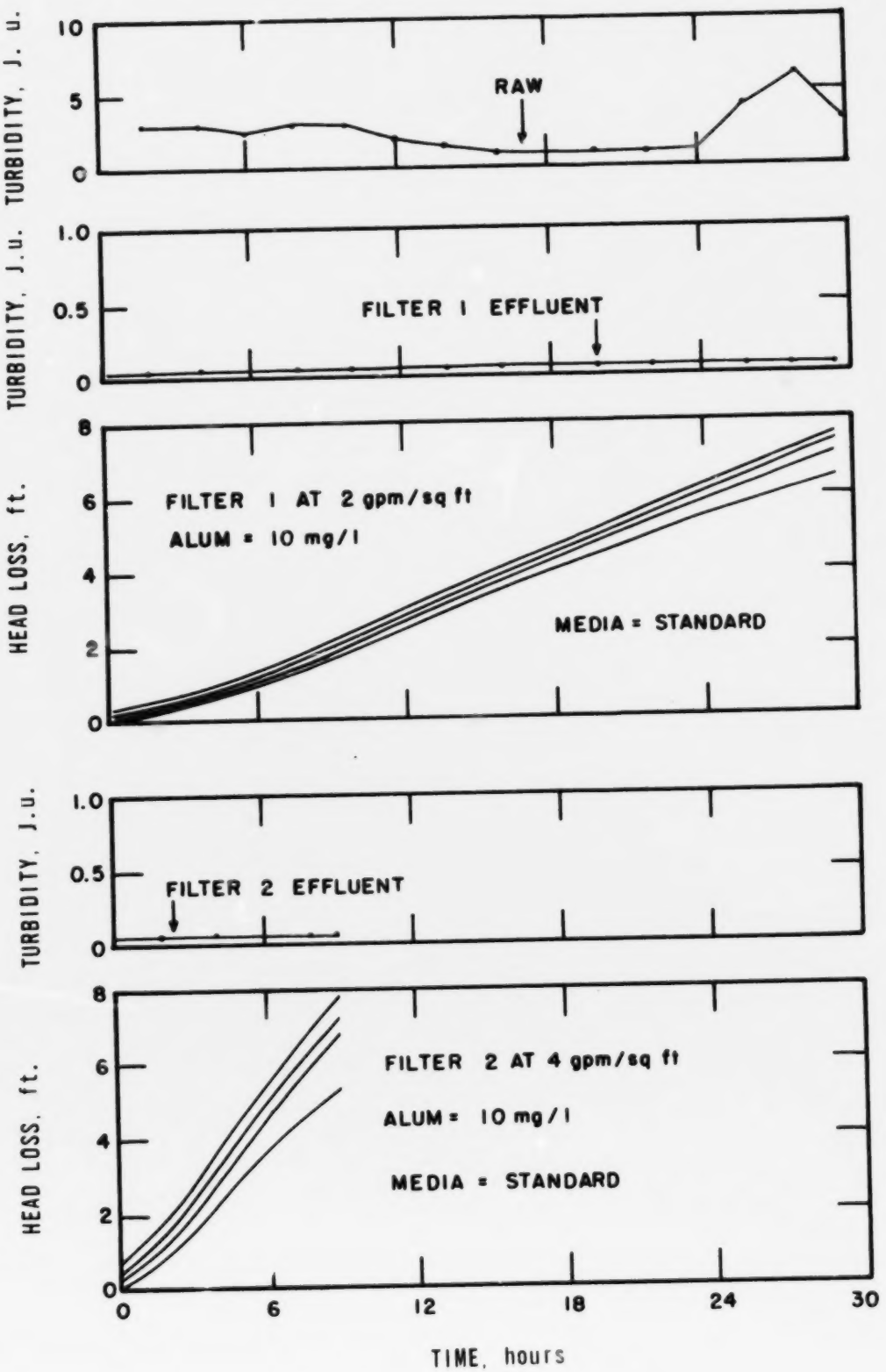

Figure 12. Head loss and turbidity values for run 3 of summer series. Aug. 22, 1964.

Figure 14 shows run 5 in which filter 1 produced a very good effluent for 6 hours at a filtration rate of 6 gpm/ft^2. Filter 2 at 2 gpm/ft^2 reached the same head loss after 19 hours and produced a similar effluent. Even though all the removal took place in the top of the coal for filter 2, it lasted slightly more than three times as long as filter 1. This was probably a result of a lower initial head loss for filter 2.

In run 6 (Figure 15) both filters produced an effluent with a turbidity less than 0.1 J.u. Filter 1 at 4 gpm/ft^2 operated 8.5 hours, and filter 2 at 2 gpm/ft^2 was stopped at a similar head loss after 23 hours. The higher filtration rate resulted in a slightly deeper penetration of the floc, but not enough to appreciably lengthen the run since the length of run for filter 2 was more than twice that of filter 1.

In the last run of the summer series (Run 7, Figure 16) both filters were operated at the same rate, 4 gpm/ft^2 with filter 1 receiving 10 mg/liter of alum and filter 2 receiving 5 mg/liter. Although there was no noticeable difference in the effluent turbidity, the floc distribution in the filter was markedly affected by the lower alum dose of filter 2. After 9 hours of operation, filter 1 had a total head loss of only 2.1 feet. Throughout the run the distribution of floc removal in filter 2 utilized much more of the bed depth than filter 1 or any of the other filter runs in this series. If filter 2 had been continued to a 7-foot head loss, there may have been a breakthrough during the run inasmuch as a considerable amount of floc was being removed by the sand layer. This is shown by the incremental head loss of 1.6 feet

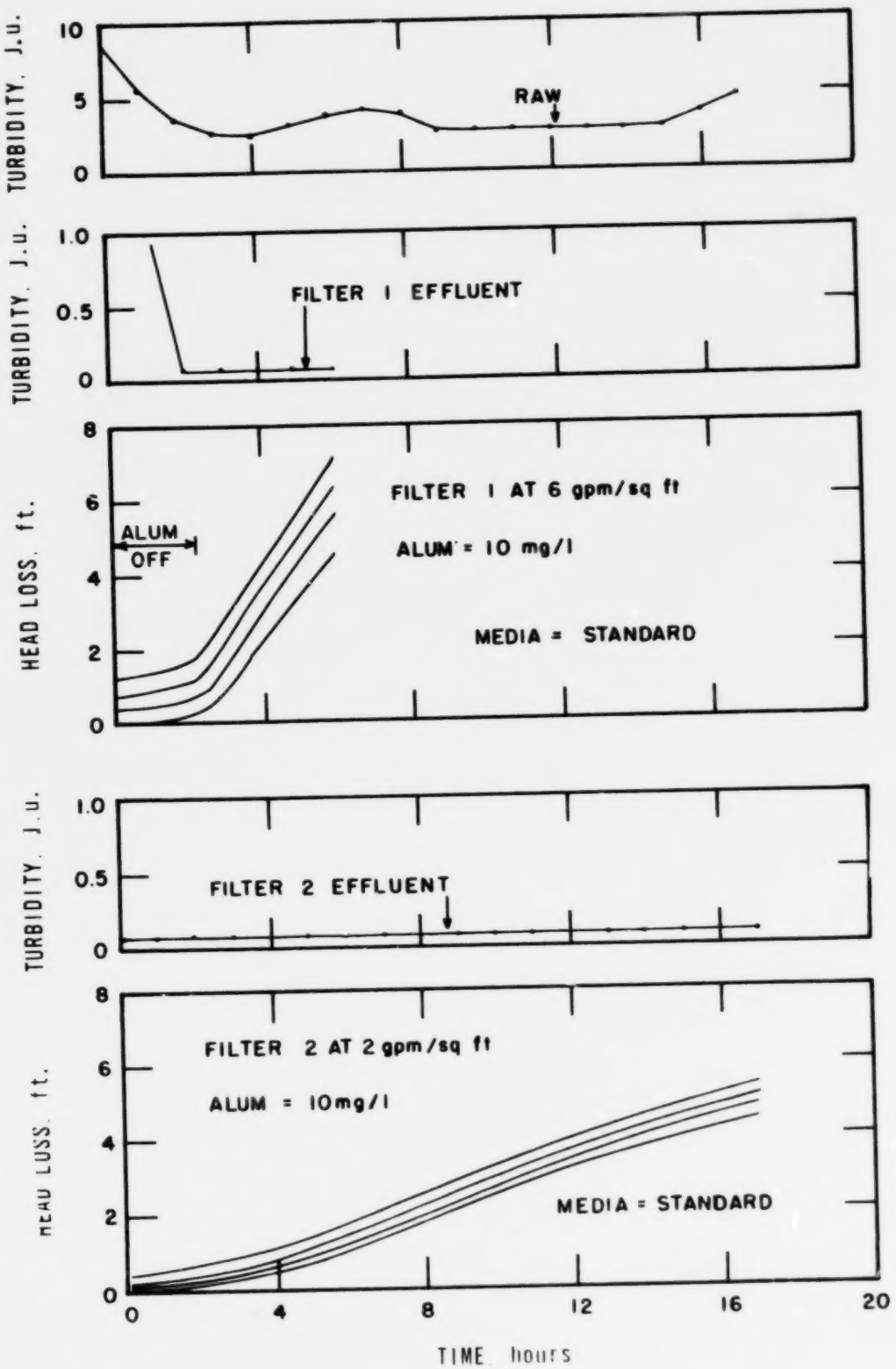

Figure 13 Head loss and turbidity values for run 4 of summer series. Aug. 24, 1964.

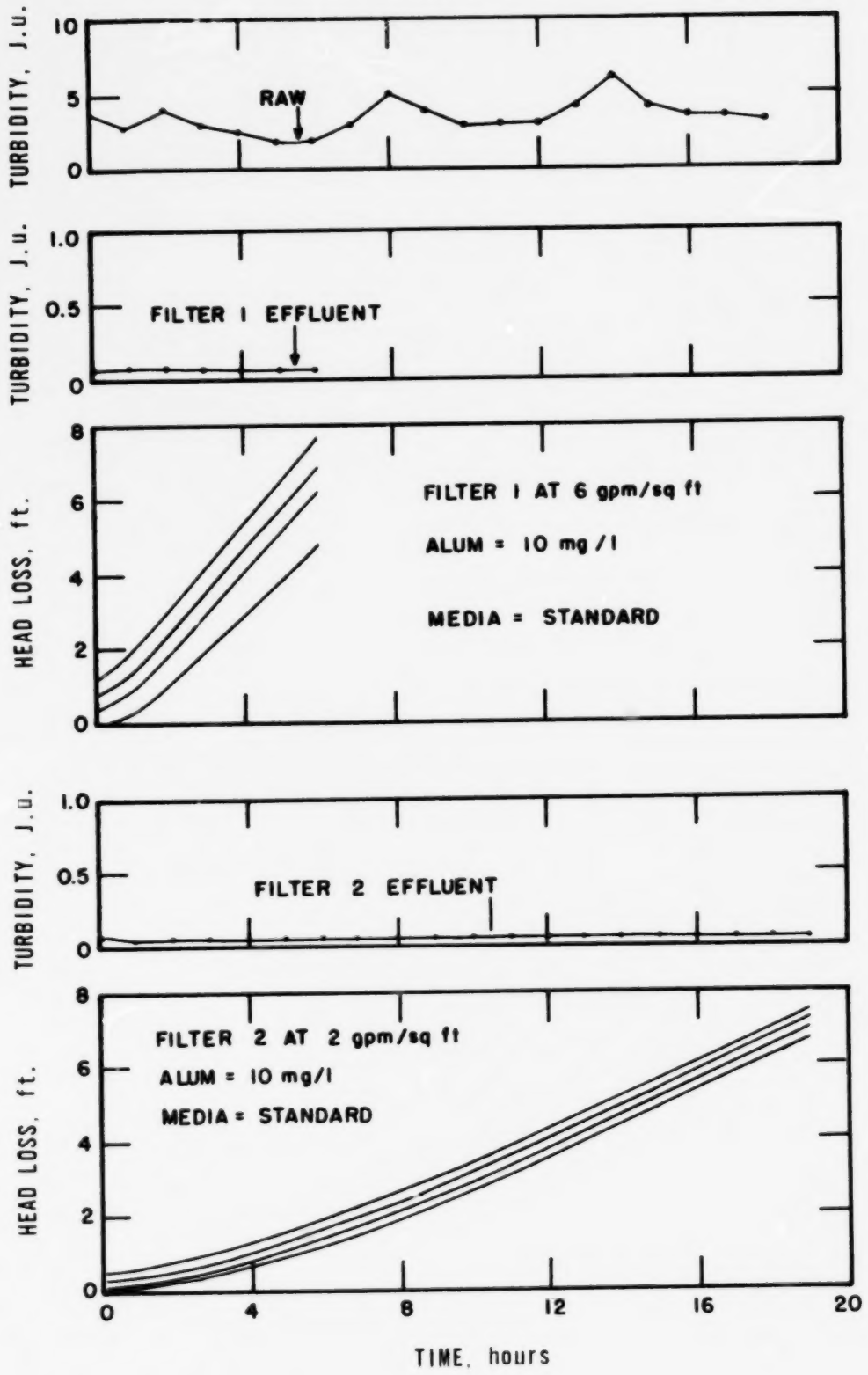

Figure 14. Head loss and turbidity values for run 5 of summer series, Aug. 25, 1964.

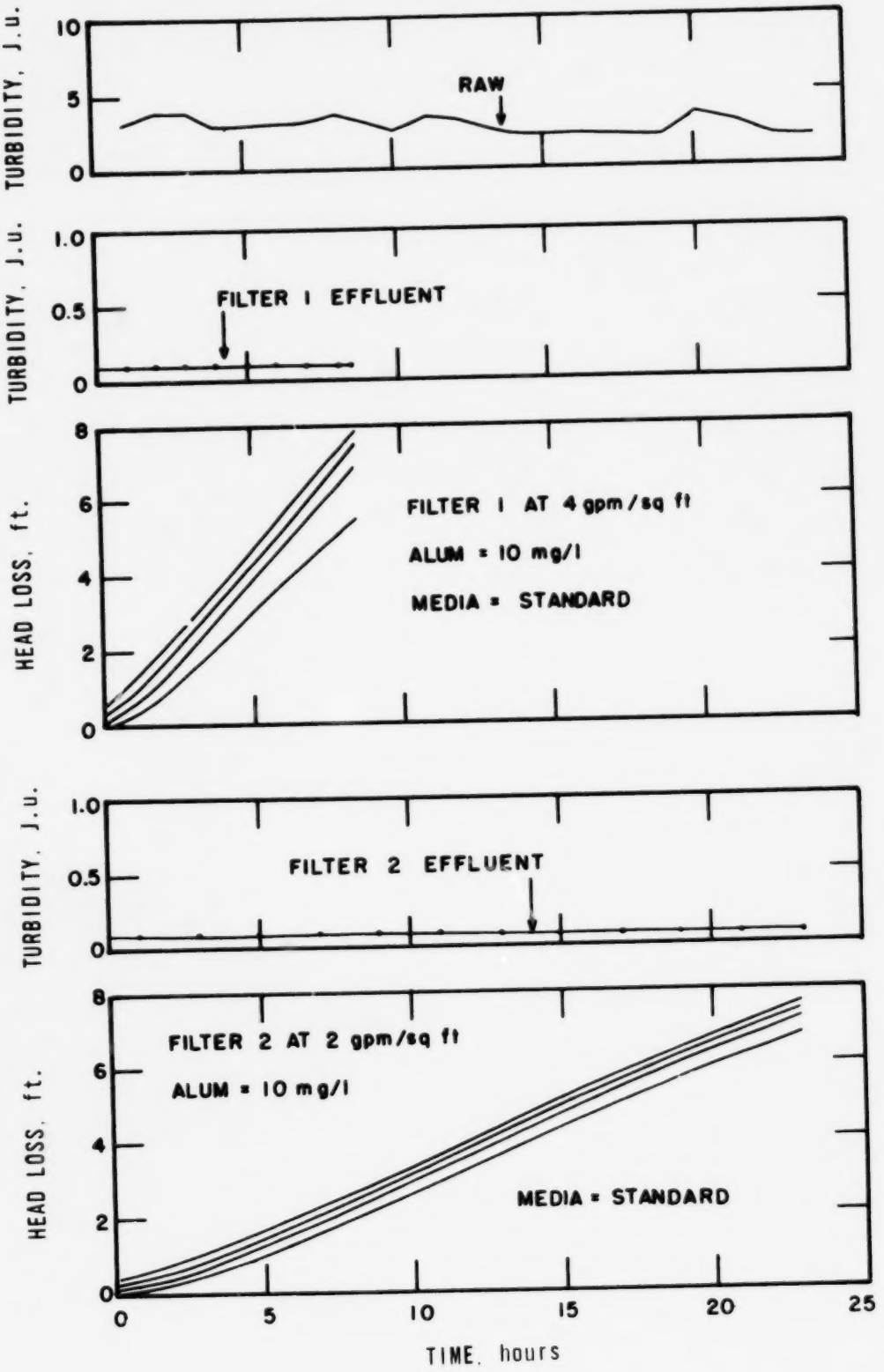

Figure 15. Head loss and turbidity values for run 6 of summer series, Aug. 26, 1964.

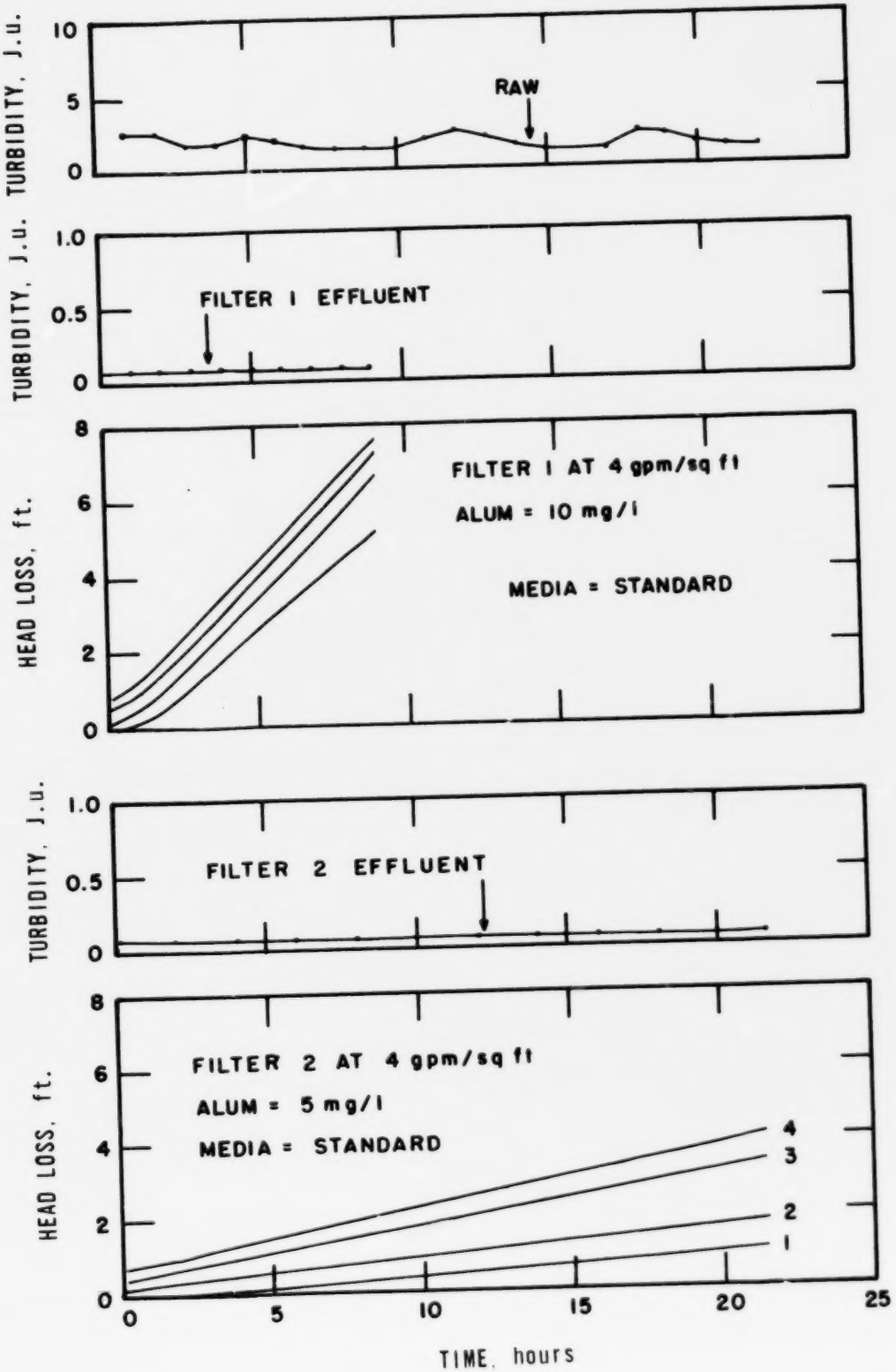

Figure 16. Head loss and turbidity values for run 7 of summer series, Aug. 27, 1964.

between pressure taps 2 and 3. Judging from this run, it is quite probable that a lower alum dose in many of the first six runs of this series would have achieved the desired clarity and markedly lengthened the filter run. Another point illustrated by this run is that alum in excess of the amount needed for obtaining the desired clarity strengthens the floc much as a filter aid does. The extra alum also results in more suspended solids, which have to be removed by the filter.

Fall Series

From November 18 through 26, 1964, the second or fall series of runs was conducted. This is the period of the year when more turbidity is generally encountered in the raw water because high winds accompany frequent storms.

One change was made in the experimental conditions used in the first series of runs. Since both the coal and sand size ranges were very narrow in the first series of runs, the media in one of the filters was replaced with coal and sand of more practical size ranges. The media in filter 2 was replaced with 6 inches of commercially available filter sand (e.s. = 0.43 mm, u.c. = 1.62) and 18 inches of coal. Initially the commercially available coal had an effective size of 0.93 mm and a uniformity coefficient of 1.71; but before the coal layer was added to the small filter, some of the fines were removed. In the first two runs, filter 1 contained 18 inches of coal from which all of the particles smaller than 1.0 mm had been removed by sieving and 6 inches of sand. In later runs in this series coal sizes varied because coal particles finer than 1.2, 1.4, and 1.7 mm were removed at different times prior to adding the 18 inches of coal.

Figure 17 shows the first run of the fall series. Filter 2 was not operated because of difficulties with the effluent rate-of-flow controller. Even though the raw water or filter influent turbidity was higher than for any run in the summer series, 10 mg/liter of alum and a 4 gpm/ft^2 filtration rate still resulted in an effluent turbidity below 0.1 J.u. Because of the wider particle size range of the coal (see Table 2), a more effective use was made of the coal layer in this run than in any of the previous runs. As shown by the head-loss curves, the top 6 inches of the coal had a head loss of 2.9 feet upon termination of the run and the next 12 inches of the coal (between head-loss taps 1 and 2) had an incremental head loss of 3.3 feet.

Both filters in run 2 (Figure 18) produced a very clear water, with filter 1 lasting over 30 percent longer than filter 2 because of the coal size. The combination of coal size, filtration rate, and alum dose for filter 1 resulted in a much better distribution of head loss. The first 6 inches of coal had a headloss of 2.6 feet, or 0.43 foot of head loss per inch of bed depth, and the next 12 inches of coal had an incremental head loss of 4.1 feet (between taps 1 and 2), or 0.35 foot per inch of bed depth.

Before the start of run 3, the media from filter 1 was replaced with new sand plus coal from which particles less than 1.2 mm had been removed. As with filter 1 in the first two runs, the larger coal particles allowed a deeper penetration of the floc into the coal layer without any noticeable deterioration in the effluent quality as measured by turbidity (Figure 19).

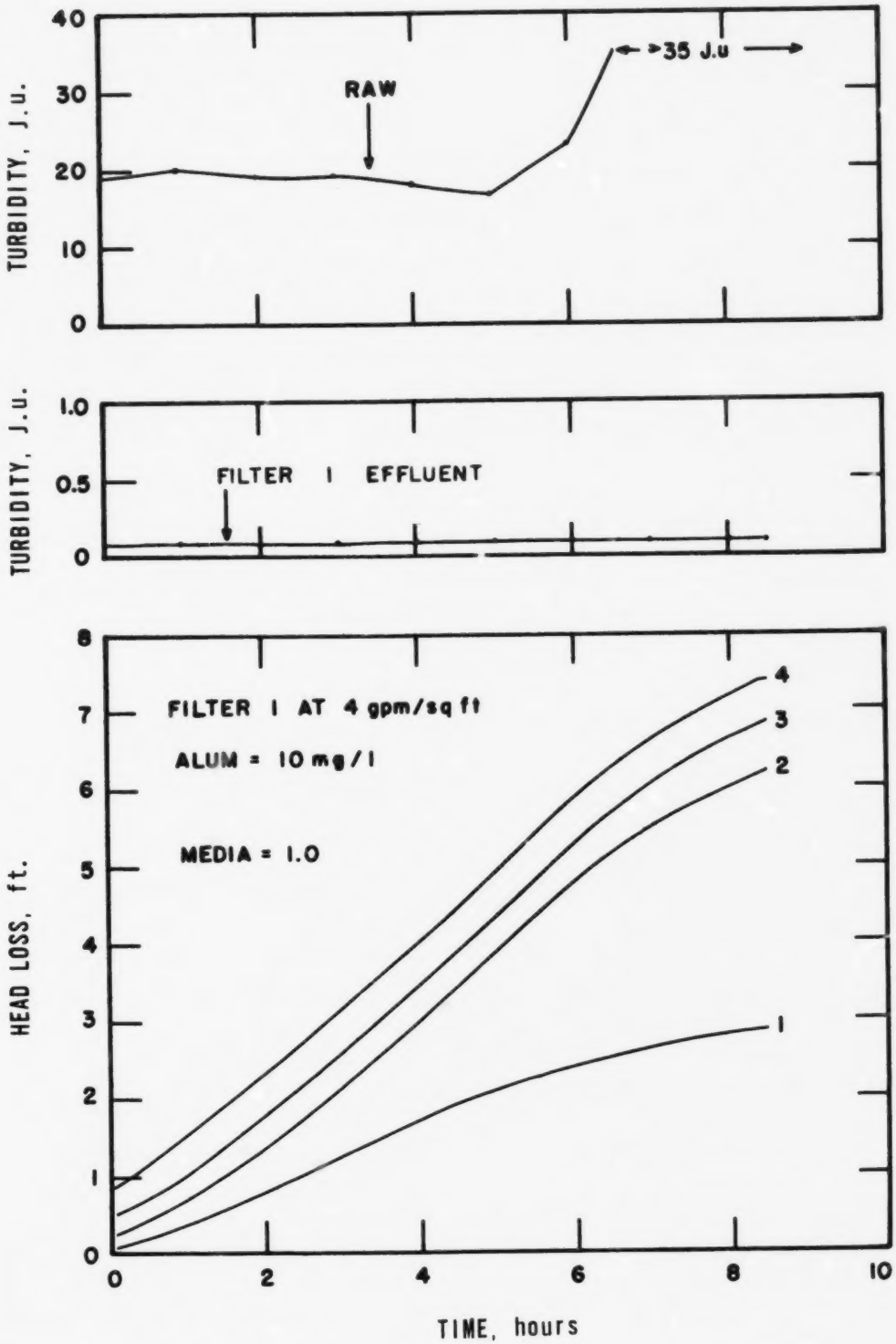

Figure 17. Head loss and turbidity values for run 1 of fall series Nov. 18, 1964.

The influence of raw water turbidity on length of run is readily seen by comparing runs 2 and 3 (Figure 18 and 19). Both runs at 4 gpm/ft^2 and 10 mg/liter alum produced an effluent with a turbidity of about 0.1 J.u. The average raw water turbidity in run 3 was about three times that of run 2, and this resulted in a shortening of the run for filter 2 from 9 to 6.4 hours. Filter 1 in run 3 contained a larger size coal than it did in run 2, but the length of run was still reduced from 13 to 9 hours.

For run 4, which is shown in Figure 20, the alum was reduced to 5 mg/liter and the filtration rate was increased to 6 gpm/ft^2. The reduction in alum coupled with an increase in both raw water turbidity to over 35 J.u. and filtration rate resulted in filter effluent turbidities higher than those for any of the previous runs. Filter 2 produced an effluent with a turbidity of 0.5 J.u. or less, but filter 1 with the larger media produced an effluent with a turbidity range of 0.3 to 1.9 J.u. This passage of turbidity by filter 1 is also indicated by the incremental head-loss curves, which show a penetration of floc into both the upper (between taps 2 and 3) and lower half (between taps 3 and 4) of the sand layer.

After the alum dose was increased 10 mg/liter, run 5 (Figure 21) was started with the filtration rate held at 6 gpm/ft^2. Even though the raw water turbidity was greater than 35 J.u., both filters produced an effluent with a turbidity of 0.1 J.u.; but the length of run was reduced markedly for both filters as compared to the previous run. The floc penetrated deeper in filter 1 than in filter 2, and, thus, an increase in length of run resulted for filter 1. Table 4 shows the incremental head losses for both filters for run 5.

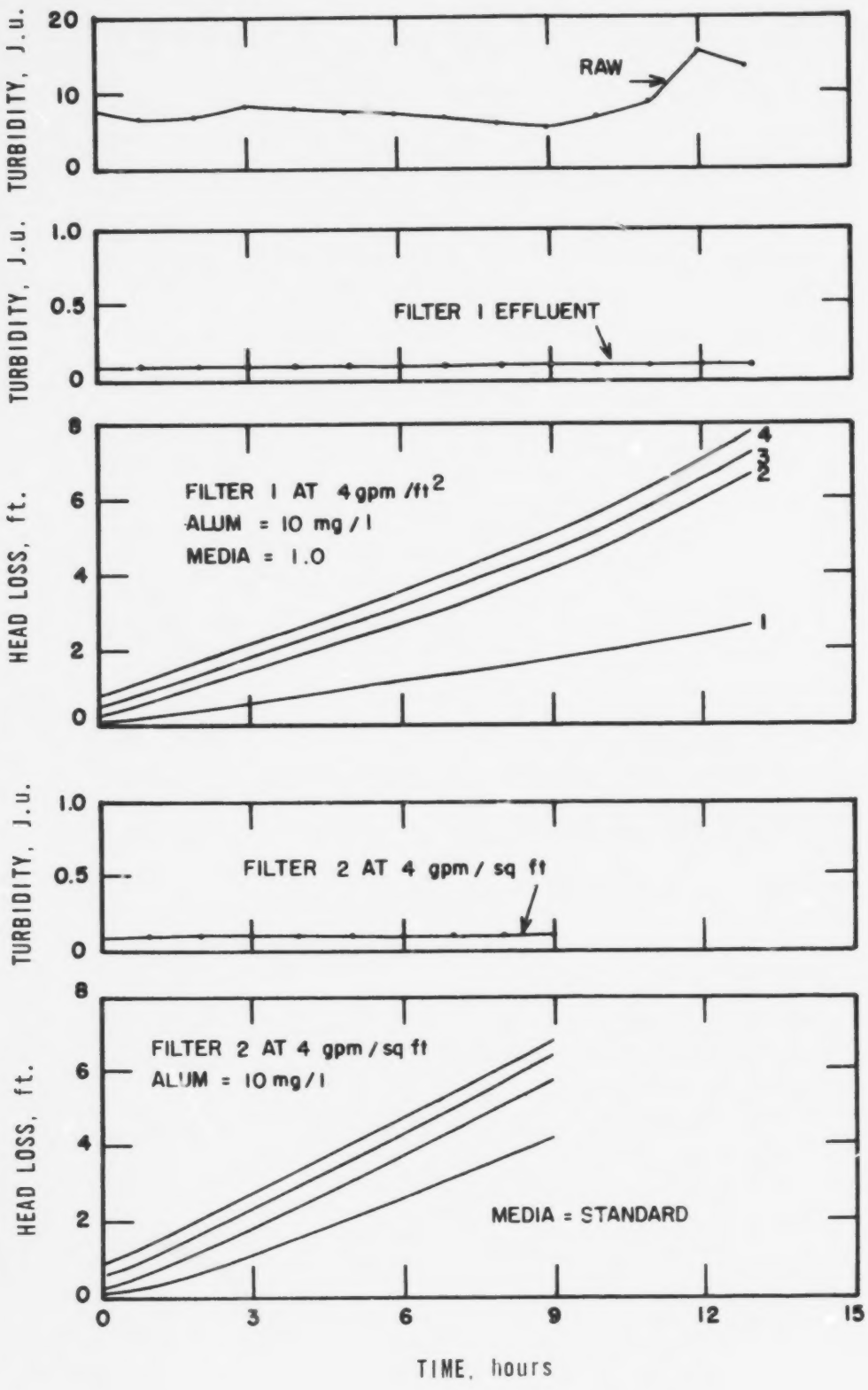

Figure 18. Head loss and turbidity values for run 2 of fall series, Nov. 19, 1964.

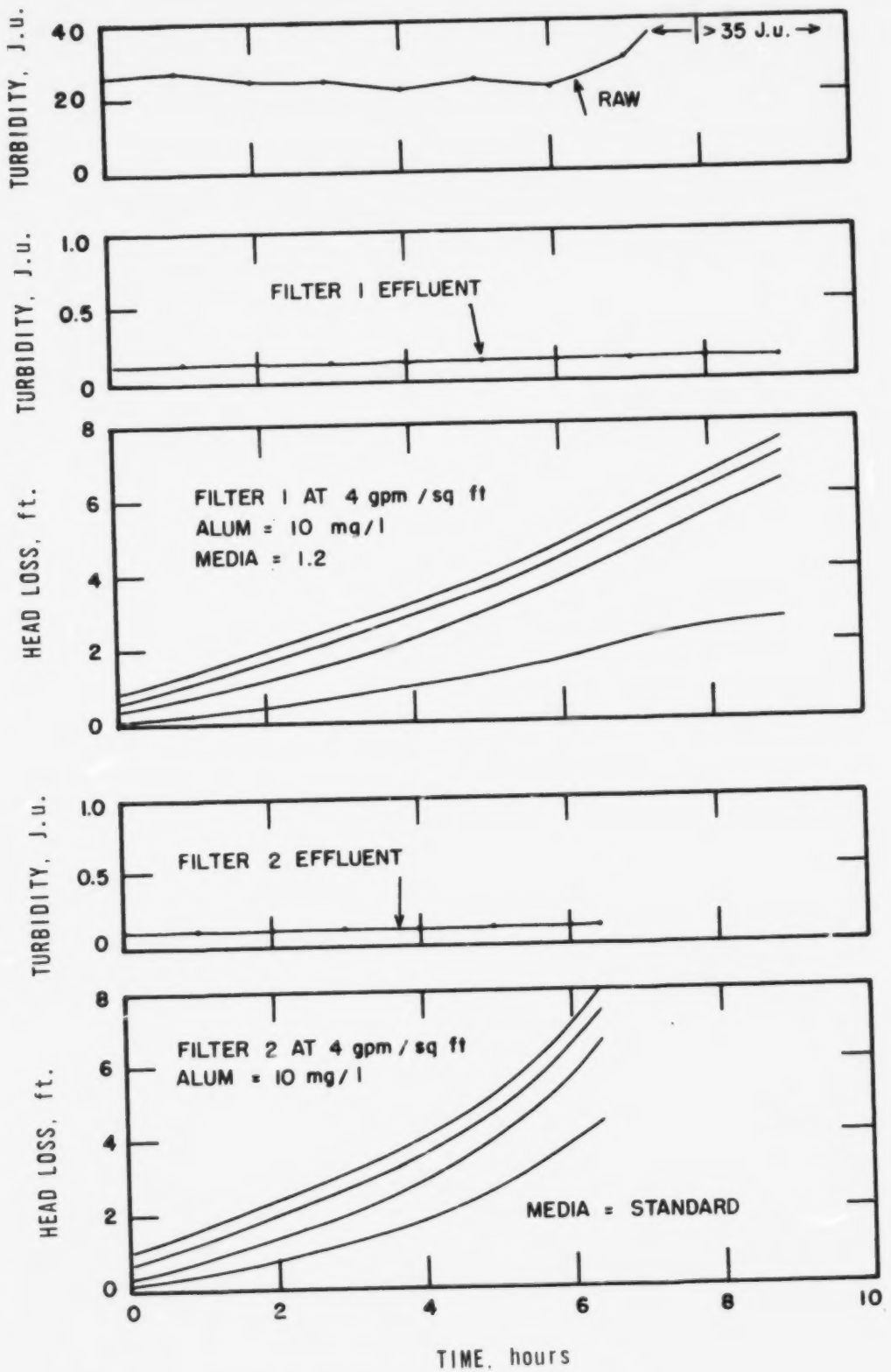

Figure 19. Head loss and turbidity values for run 3 of fall series, Nov. 20, 1964.

Table 4. INCREMENTAL HEAD LOSSES FOR RUN 5

Bed depth, inches	Filter 1		Filter 2	
	Δh_L	$\Delta h_{L/in.}$	Δh_L	$\Delta h_{L/in.}$
0-6	1.3	0.22	3.0	0.50
6-18	3.5	0.29	2.5	0.21
18-21	1.7	0.57	1.0	0.33

After 5 hours of operation, the top 6 inches of coal in filter 1 had a head loss of 1.3 feet, or 0.22 foot per inch of bed depth. The same portion of filter 2 had a head loss of 3.0 feet after 3 hours of operation, or 0.50 foot per inch of bed depth. Between pressure taps 1 and 2, the 6- to 18-inch segment of the bed, the head loss was 3.5 feet for filter 1, or 0.29 foot per inch of bed depth. The corresponding incremental head loss for filter 2 was 0.21 foot per inch. Filter 1 gave the first filter run in this 1-year study in which the average head loss per inch of bed depth was greater for the 6- to 18-inch layer than it was for the 0- to 6-inch layer. The increased removal by the lower portion of the coal layer was attributed to a more uniform size of coal in the upper layer of coal and to a zone in which the coal and sand were mixed.

After the media in filter 1 was replaced again, this time with a coal layer from which all particles smaller than 1.4 mm had been removed, run 6 was started. Both filters were operated at 2 gpm/ft^2, the alum dose was 10 mg/liter, and the raw water turbidity varied from 25 to over 50 J.u. As shown in Figure 22, the effluent turbidity was less than 0.5 J.u. Filter 1 with the coarser coal lasted 22 hours as a result of a good

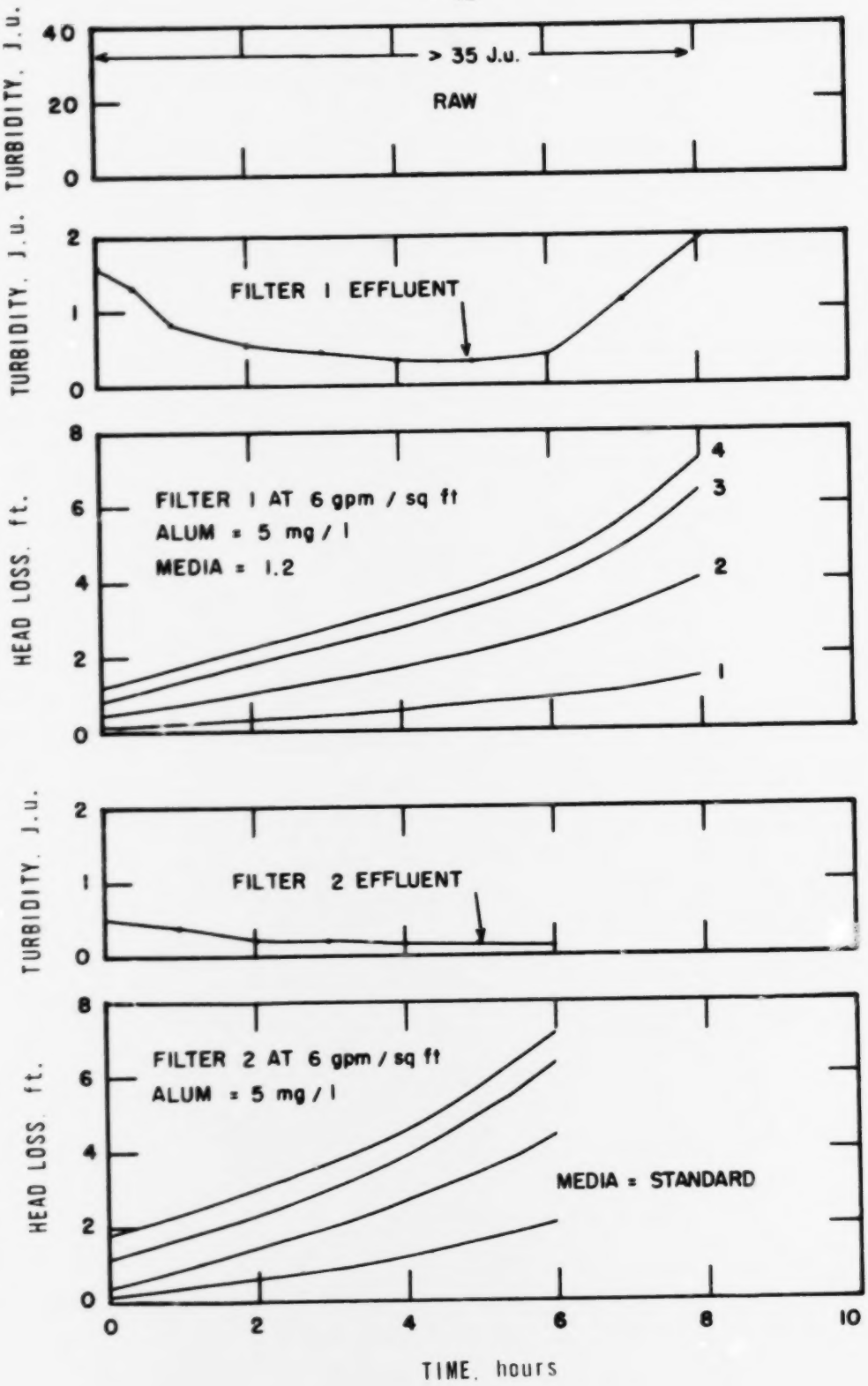

Figure 20. Head loss and turbidity values for run 4 of fall series, Nov. 21, 1964.

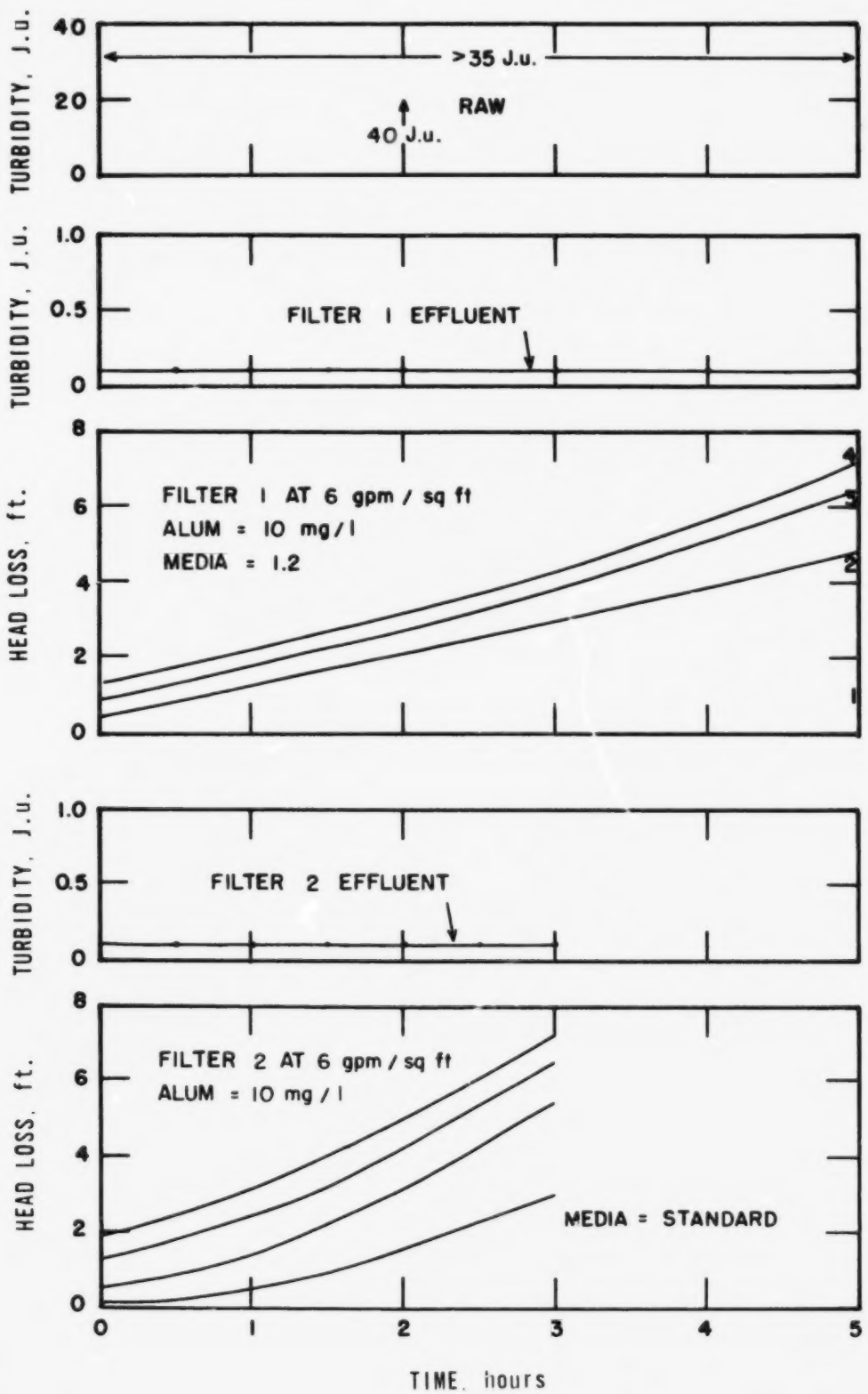

Figure 21. Head loss and turbidity values for run 5 of fall series, Nov. 22, 1964.

distribution in floc removal, whereas filter 2 with the "standard" media lasted only 13 hours. Both filters were stopped because of excessive head loss, not turbidity breakthrough.

A lower raw water turbidity during run 7 resulted in a reduction in the filter effluent turbidities, especially during the early part of the run, as shown by Figure 23. In this run, filter 2 containing the standard media had a higher utilization of the coal layer in removal of the floc than previous runs in which similar media were used. The top 6 inches of coal had a head loss of 2.3 feet when the total head loss was 7 feet, whereas in run 6 the head loss in the top 6 inches was 4.2 when the total was 7 feet. Filter 1 had a deep penetration of the floc into the bed; much of the removal was in the zone of mixed coal and sand. The filtration rate of 6 gpm/ft^2 resulted in excessive penetration of the floc into the lower 6 inches of the bed. Between pressure taps 2 and 3 the incremental headloss was 1.7 feet, or 0.57 foot per inch of bed depth as compared to 0.32 foot per inch of depth between taps 1 and 2. If the floc had been strengthened and retained higher in the bed, the length of run could probably have been increased.

Prior to startup of run 8, the media in filter 1 were changed again. This time only coal particles equal to or greater than 1.7 mm were used. Figure 24 shows that this larger coal allowed a greater passage of material by filter 1 than the standard media of filter 2, although the effluent turbidity was still held at or below 0.5 J.u. by filter 1. This increase in coal size had an additional effect on

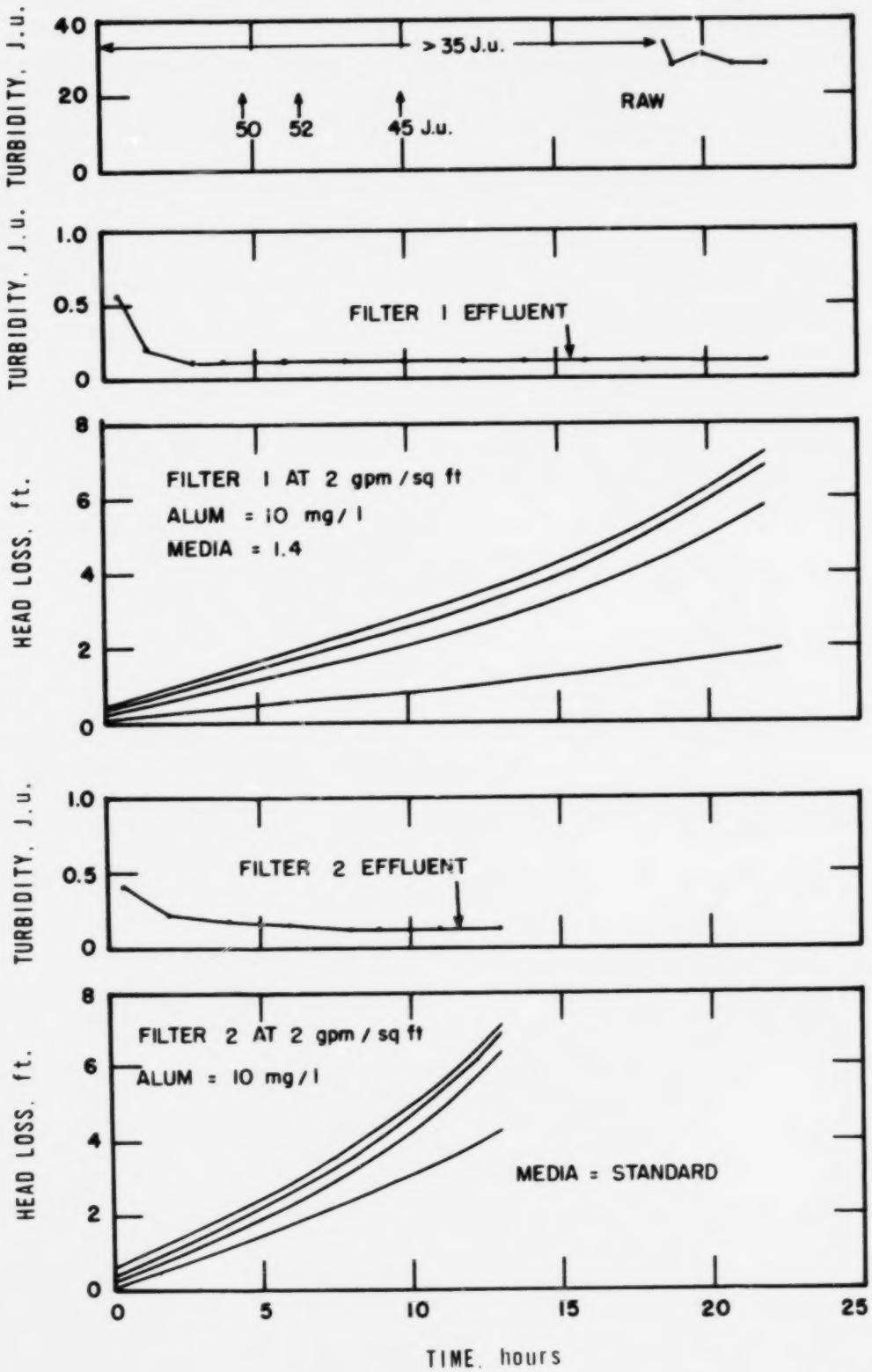

Figure 22. Head loss and turbidity values for run 6 of fall series. Nov. 23, 1964.

the length of run over the coal size used in the previous run. After 20 hours of operation, filter 1 had a total head loss of 3.0 feet compared to 7.6 feet for filter 2. The larger effective size and smaller uniformity coefficient (see Table 2) of this coal layer allowed the upper portion of the sand layer to penetrate higher into the coal layer; this difference accounts for the much more efficient use of the filter.

In run 9, shown in Figure 25, filter 1 with the coal greater than 1.7 mm allowed the floc to penetrate to the sand layer when operated at 6 gpm/ft^2. The head loss per inch of bed depth for the bed layer between taps 2 and 3 (3 inches of bed depth) was much higher than for any other portion of the bed. This in turn reduced the length of run advantage of filter 1 over filter 2, although both filters produced an acceptable effluent from a turbidity standpoint.

A reduction in filtration rate to 4 gpm/ft^2 yielded the data shown in Figure 26 (run 10). During this run, the last of the fall series, the highest influent turbidity of the study was recorded. The value of 58 J.u. was measured after 6 hours of operation. Filter 2 produced an effluent with 0.1 J.u. of turbidity for the 8-hour run. Filter 1 produced a similar effluent for 9 hours, and then a breakthrough occurred. A small amount of filter aid would probably have eliminated the breakthrough and lengthened the run by keeping more of the material in the upper portion of the bed.

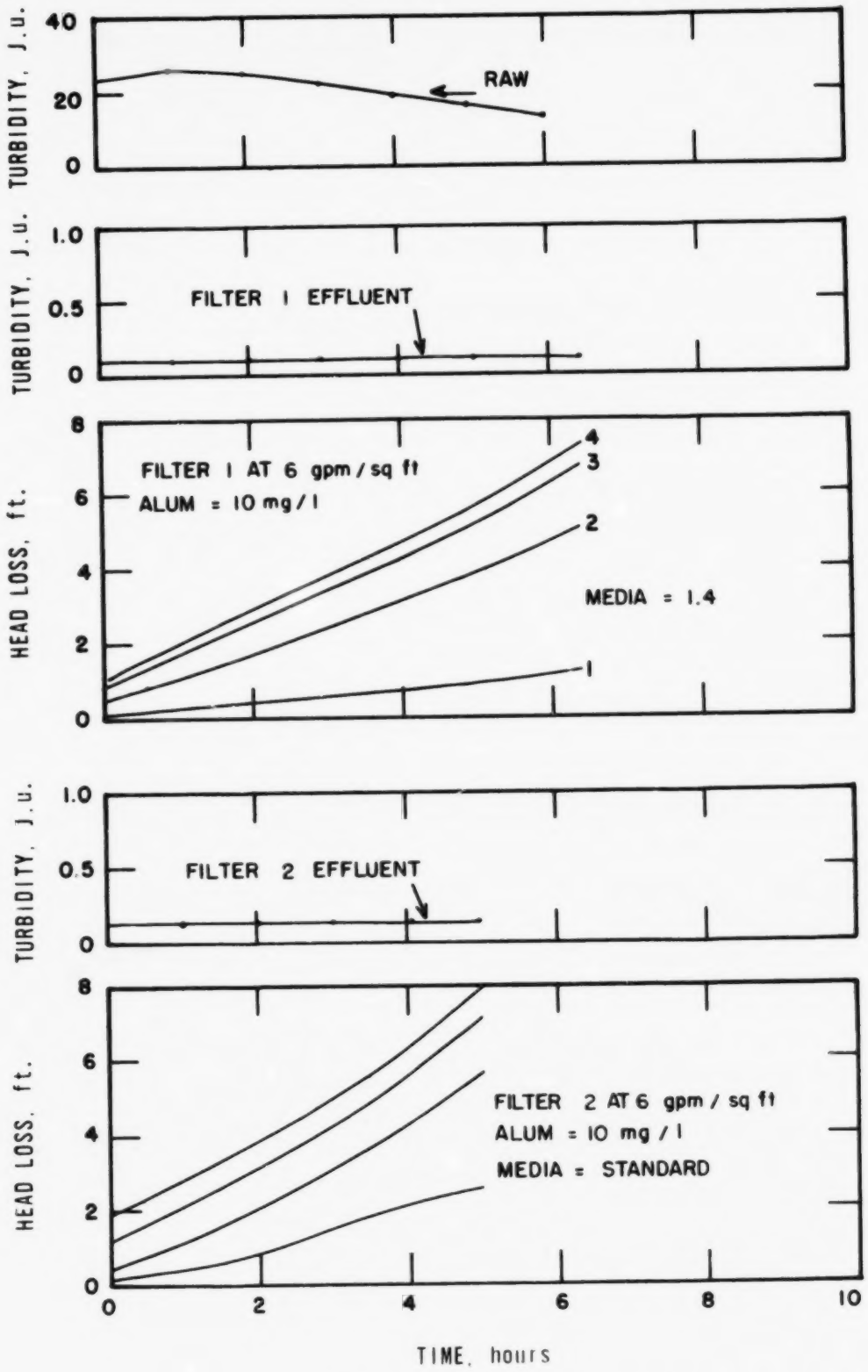

Figure 23. Head loss and turbidity values for run 7 of fall series. Nov. 24, 1964.

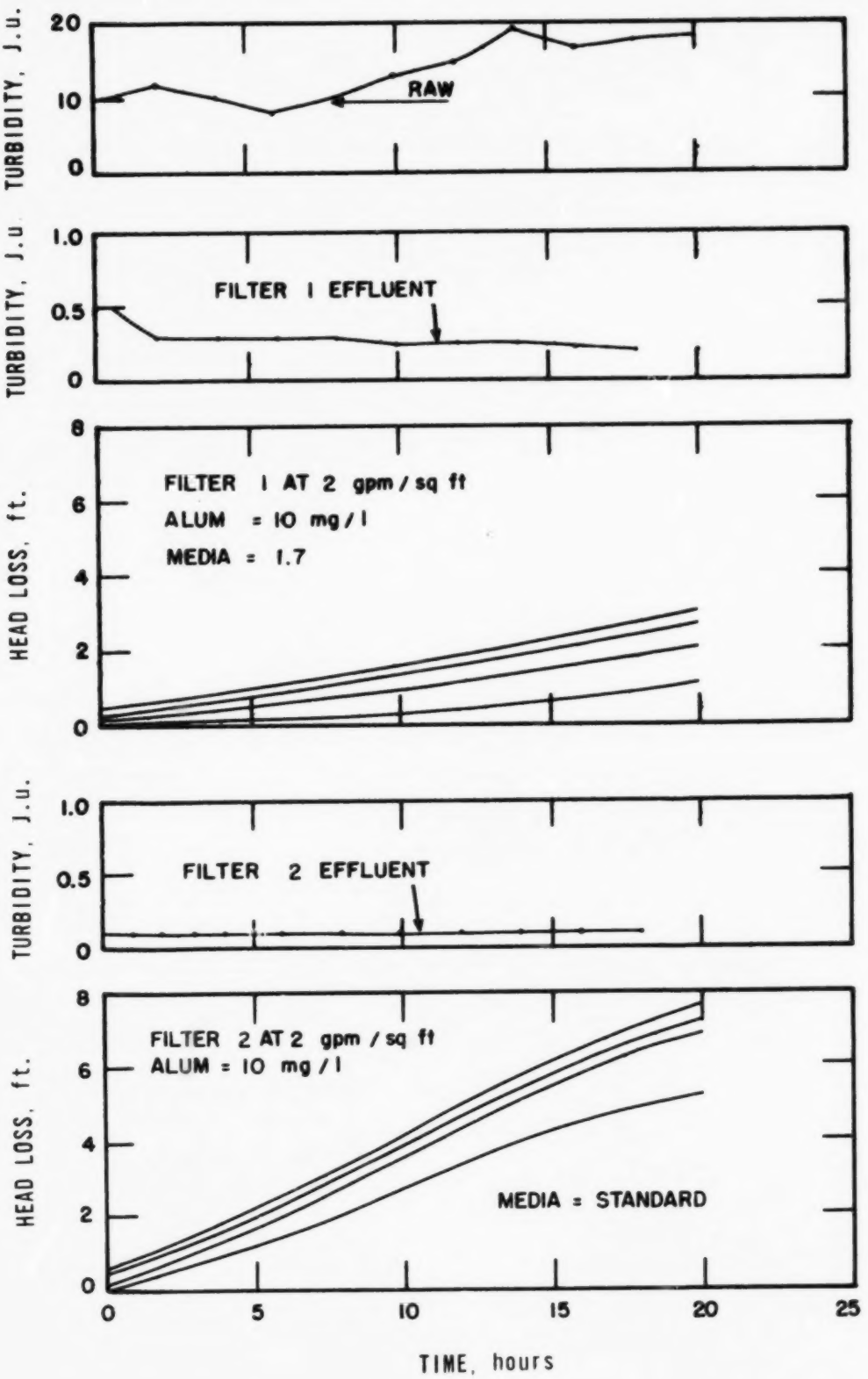

Figure 24. Head loss and turbidity values for run 8 of fall series, Nov. 25, 1964.

Winter Series

The winter series of six runs was conducted from February 11 through 16, 1965. This period was indicative of the winter season in that the raw water was cold (Table 1) and low in turbidity. Filter media used in this series were similar to those used during the fall series. Filter 1 contained the standard media, and filter 2 at different times contained sand plus coal larger than 1.0 or 1.4 mm. In the first run, shown in Figure 27, the alum dose was 10 mg/liter and the filtration rate for both filters was 2 gpm/ft^2. Both filters produced an effluent with a turbidity of about 0.1 J.u. After 19.5 hours of operation, filter 1 had a total head loss of 7.0 feet whereas the head loss for filter 2 was only 3.8 feet. Although filter 1 appeared to have a distribution of removal throughout the coal layer, filter 2 had a much lower head loss at the same point in time. This is attributed to the zone of mixed coal and sand in filter 2 and the larger coal size, both of which allowed floc removal to take place throughout the upper 18 inches of the filter bed. The incremental head loss between taps 1 and 2 for filter 1 probably was in the upper 3 to 6 inches of that 12-inch segment.

A comparison of the incremental head-loss distribution in filter 1 with the distributions obtained during the summer series in filter 1, run 3 (Figure 12); filter 2, run 4 (Figure 13); filter 2, run 4 (Figure 13); filter 2, run 5 (Figure 14); and filter 2, run 6 (Figure 15) is of interest. All of these filter runs used similar filter media; and the filtration rate, alum dose, raw water turbidity, and filter

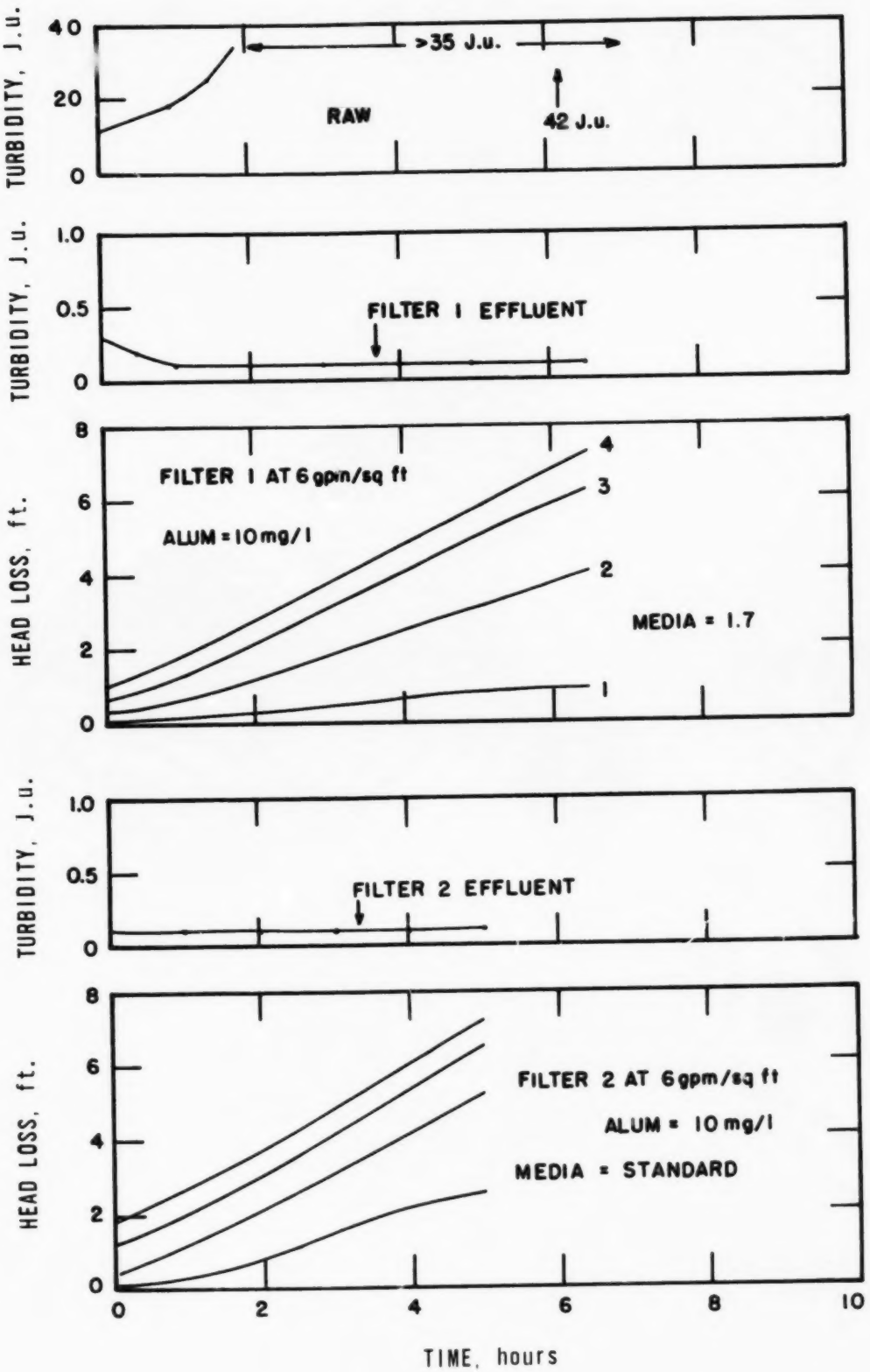

Figure 25. Head loss and turbidity values for run 9 of fall series. Nov. 26, 1964.

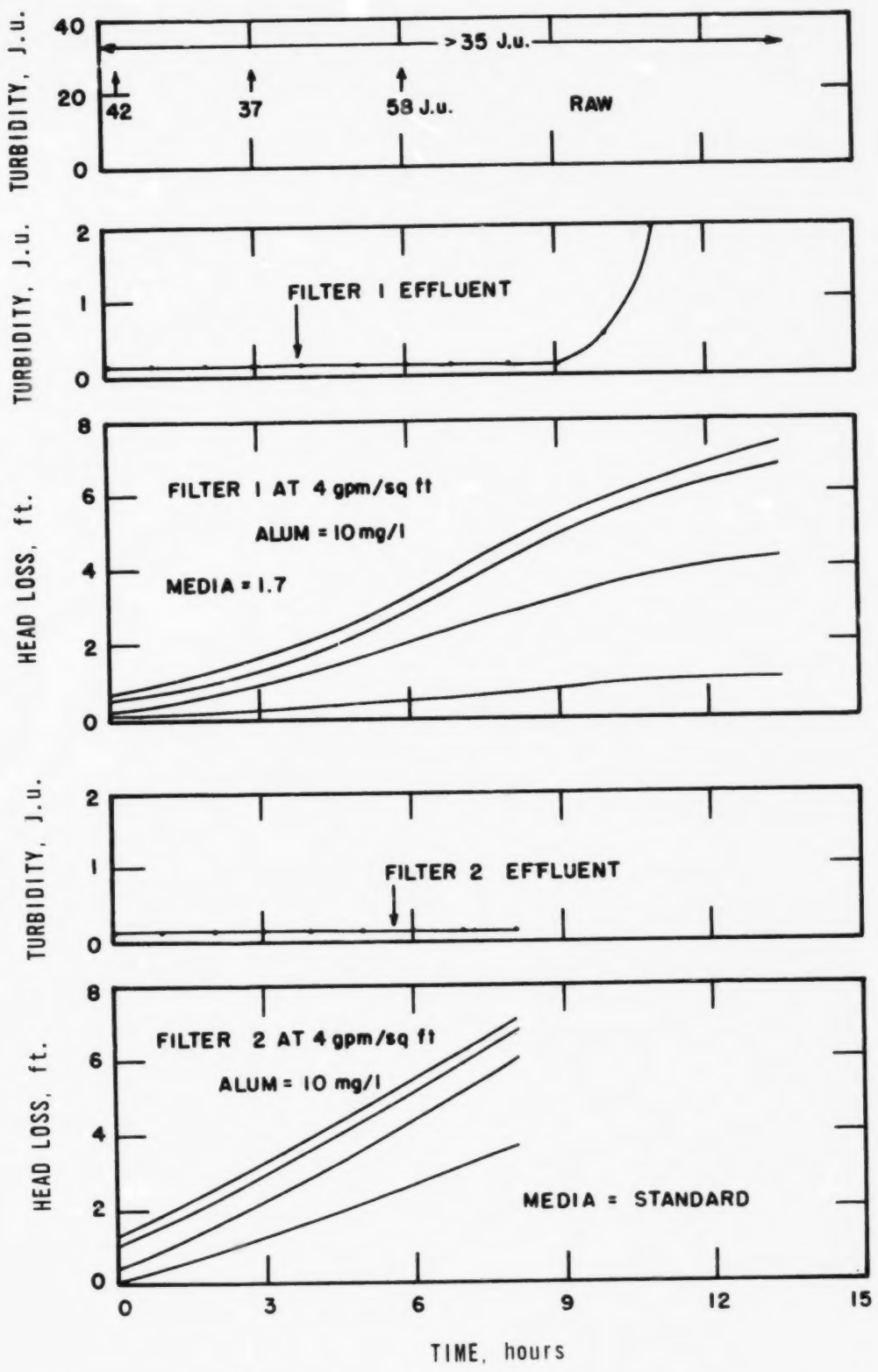

Figure 26. Head loss and turbidity values for run 10 of fall series, Nov. 26, 1964.

effluent turbidity were nearly identical. These runs also had a similar influent as measured by pH, alkalinity, and hardness. Temperature was the only measured characteristic that varied markedly; during the summer runs the influent was 68°F, whereas run 1 of the winter series had an influent temperature of 36°F. The observed difference between the four summer runs and this run was the increased penetration of the floc into the coal layer during the cold-water conditions.

The raw water turbidity remained at about 4 J.u. during run 2, and the alum dose was held at 10 mg/liter. Increasing the filtration rate to 6 gpm/ft^2 gave the results shown in Figure 28. Both filters produced an effluent with a turbidity below 1.0 J.u., but the effluent from filter 1 was consistently better than that from filter 2. The length of run for both filters was much less than one-third of the lengths obtained in run 1, although the only known difference was the higher filtration rate of run 2. Evidently the better distribution of floc removal due to the higher rates was more than offset by the higher initial head losses at the 6 gpm/ft^2 rate. As with the first run of the winter series, filter 1 appeared to have a deeper penetration of the floc than filter 2, run 2 (Figure 11); filter 1, run 4 (Figure 13); and filter 1, run 5 (Figure 14). These runs were similar in rate, media, etc., with the principal difference between the two seasons being temperature of the raw water.

In run 3 (Figure 29), the filtration rate was reduced to 4 gpm/ft^2 and the alum dose was maintained at 10 mg/liter. Even though the raw water turbidity increased to about 10 J.u., both filters produced an effluent generally below 0.5 J.u. in turbidity. Filter 1 effluent was slightly better than filter 2 effluent, but filter 2 lasted 2.5 hours

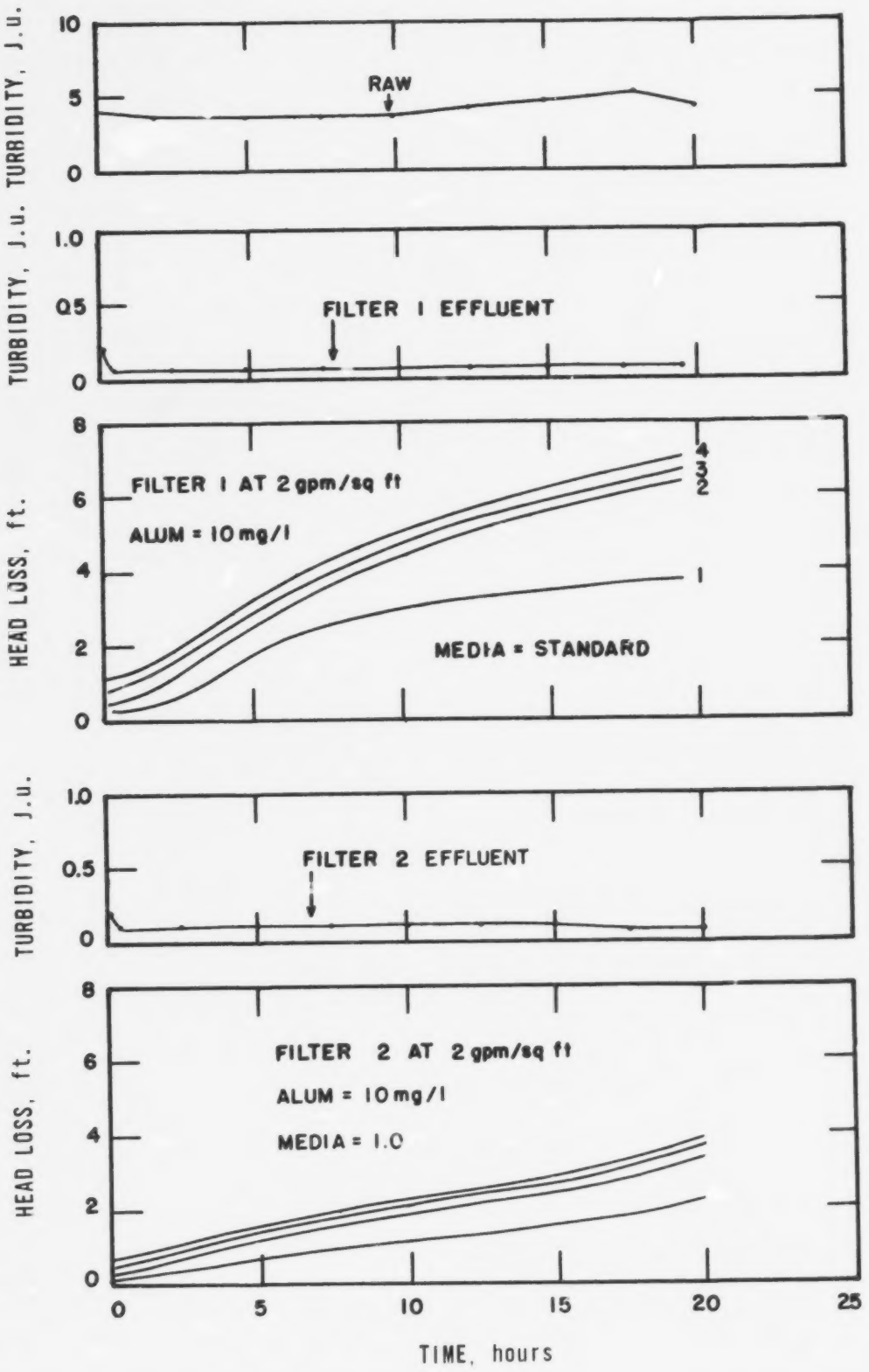

Figure 27. Head loss and turbidity values for run 1 of winter series, Feb. 11, 1965.

longer than filter 1 to the same total head loss. There were no runs during the summer series with a similar raw water turbidity for purposes of comparison.

For the last three runs of the winter series, the media in filter 2 was changed to 6 inches of sand plus 18 inches of coal greater than 1.4 mm in size. Figure 30 shows run 4, for which the filtration rate was 2 gpm/ft^2 and the alum dose 10 mg/liter. The effluent turbidities were similar, with filter 1 reaching a 7.0-foot head loss in 21 hours. After the same length of operation, filter 2 had a head loss of only 4.2 feet.

At 4 gpm/ft^2 rate, filter 1 produced an effluent with a slightly lower turbidity than that of filter 2 in run 5 (Figure 31). Filter 2 produced about 70 percent more water than filter 1 when they are compared to the same final head loss.

The last run of this series is shown in Figure 32. Filter 1 at 6 gpm/ft^2 produced a better effluent than filter 2 at the same rate, but it reached a 7-foot head loss in one-half the time that it took filter 2 to reach the same head loss.

Spring Series

The last set of eight runs was conducted from May 18 to 27, 1965. In the first four runs, both filters contained the commercial sand and coal (> 1.0 mm). The purpose of the first four runs was to check the influence of alum dose on effluent clarity and length of run. Prior to the fifth run, the media in filter 2 was replaced with coal larger than 1.4 mm and commercial sand. Runs 5 through 8 compared filter media as it influenced effluent quality and length of run. During this series filtration rates of 3 and 5 gpm/ft^2 were used instead of

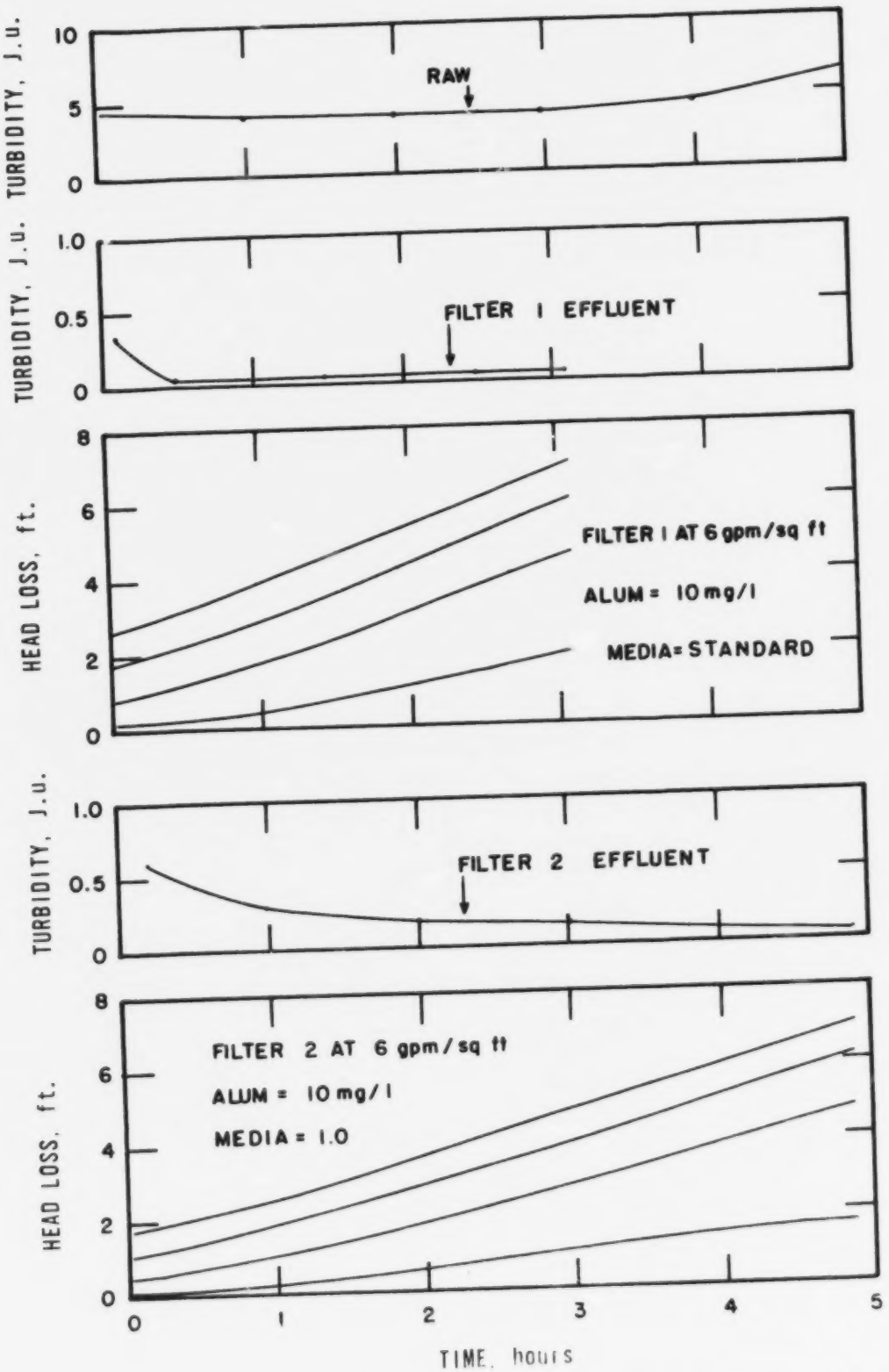

Figure 28. Head loss and turbidity values for run 2 of winter series. Feb. 12, 1965.

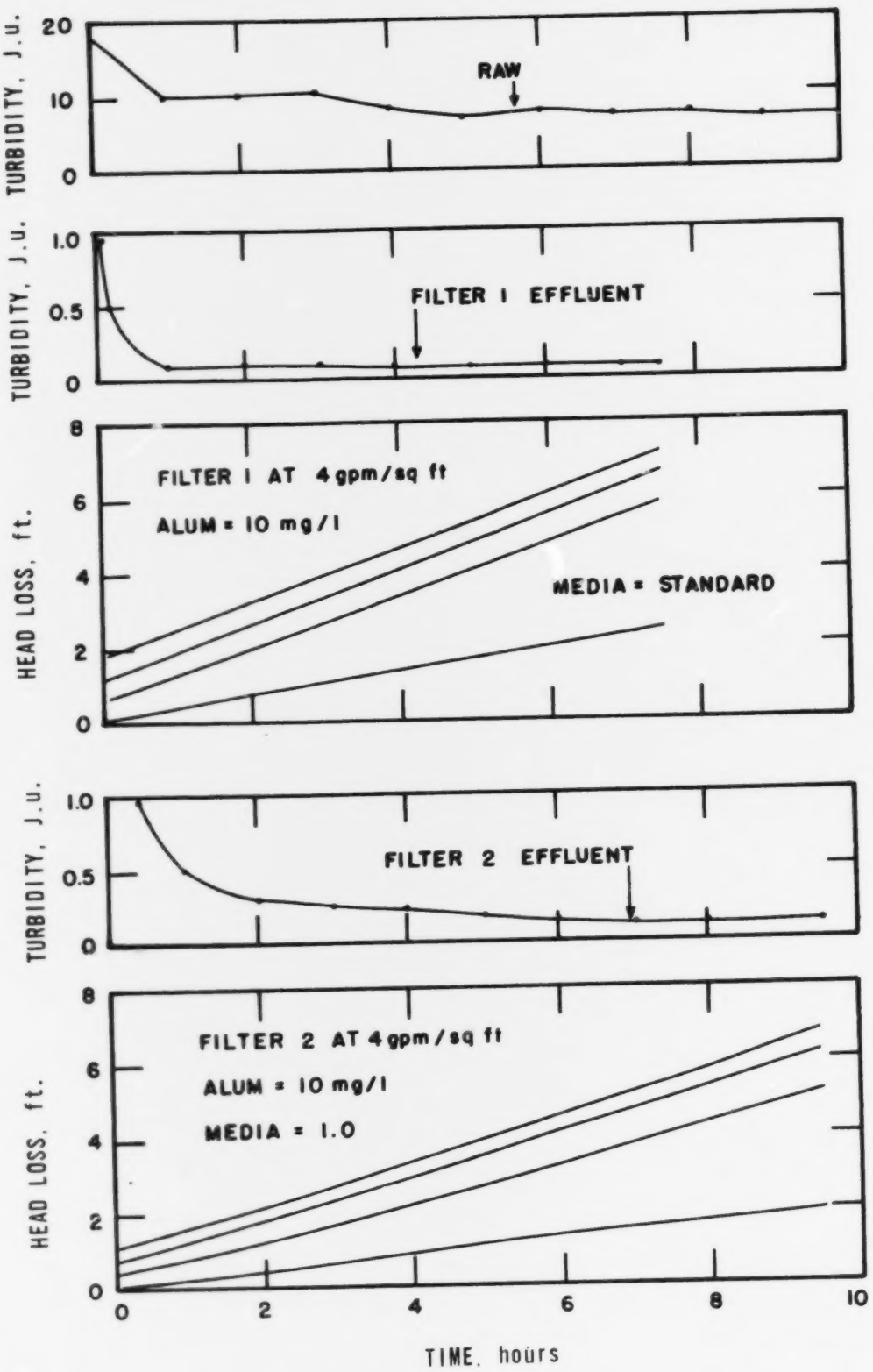

Figure 29. Head loss and turbidity values for run 3 of winter series, Feb. 13, 1965.

2, 4, and 6 gpm/ft^2 to allow more time for checking the influence of alum dose and filter media.

The first run, shown in Figure 33, shows the influence of 5 and 10 mg of alum per liter on effluent turbidity and length of run at a 3 gpm/ft^2 filtration rate. Ten mg of alum per liter resulted in an effluent turbidity of 0.1 J.u., but 5 mg/liter gave an effluent turbidity of about 1 J.u. Of interest is the influence these two doses had on the rate of head-loss buildup. After 18 hours, filter 1 with 10 mg/liter of alum had a total head loss of 6.8 feet whereas filter 2 had a headloss of only 1.8 feet. This points up again the importance of adding just enough alum to achieve the desired effluent clarity. Generally, additional alum reduces the length of run markedly because of the added solids to be removed.

Figure 34 (Run 2) shows the effect of the same alum doses at a flow rate of 5 gpm/ft^2, but with the raw water turbidity increased from about 4 J.u. in run 1 to about 20 J.u. As a result neither filter produced an effluent of the quality of run 1. Filter 1 effluent turbidity averaged about 0.4 J.u., and the effluent from filter 2 averaged about 3.5 J.u. After 6 hours of operation, filter 1 had a head loss of 6.3 feet and filter 2 had 2.6 feet. The incremental head-loss curves for both filters of run 2, and especially filter 1, reveal deep penetration of the floc into the media. Some of this increased penetration is attributable to the higher filtration rate. In this case the penetration was detrimental as shown by the head-loss curves for filter 1 of run 2. Penetration into the upper part of the sand layer (between taps 2 and 3) resulted in a shortening of the filter run. Filter 2 of run 2 also showed more removal between pressure taps 2 and 3 than was removed by filter 2 of run 1.

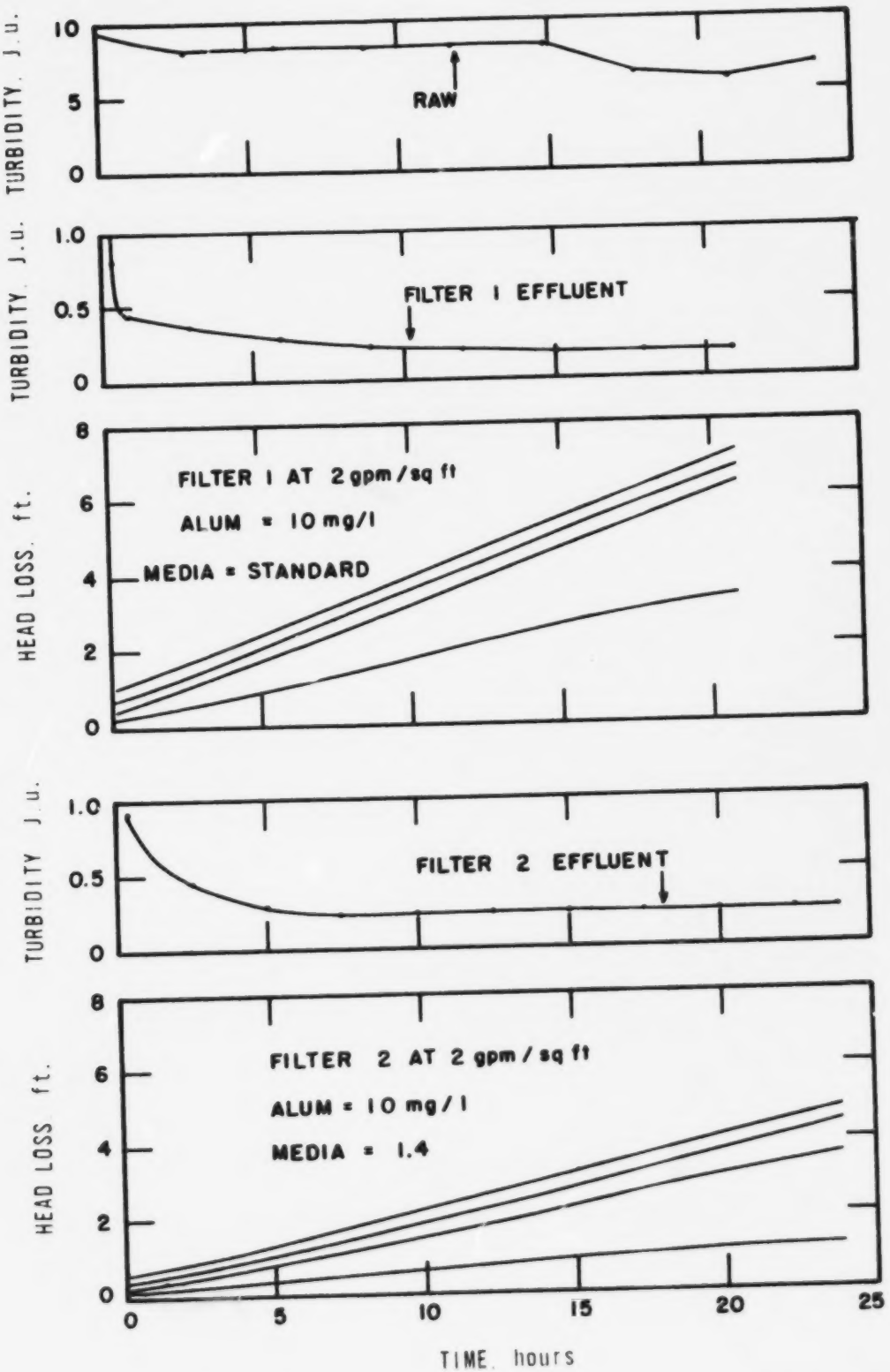

Figure 30. Head loss and turbidity values for run 4 of winter series. Feb. 14 1965

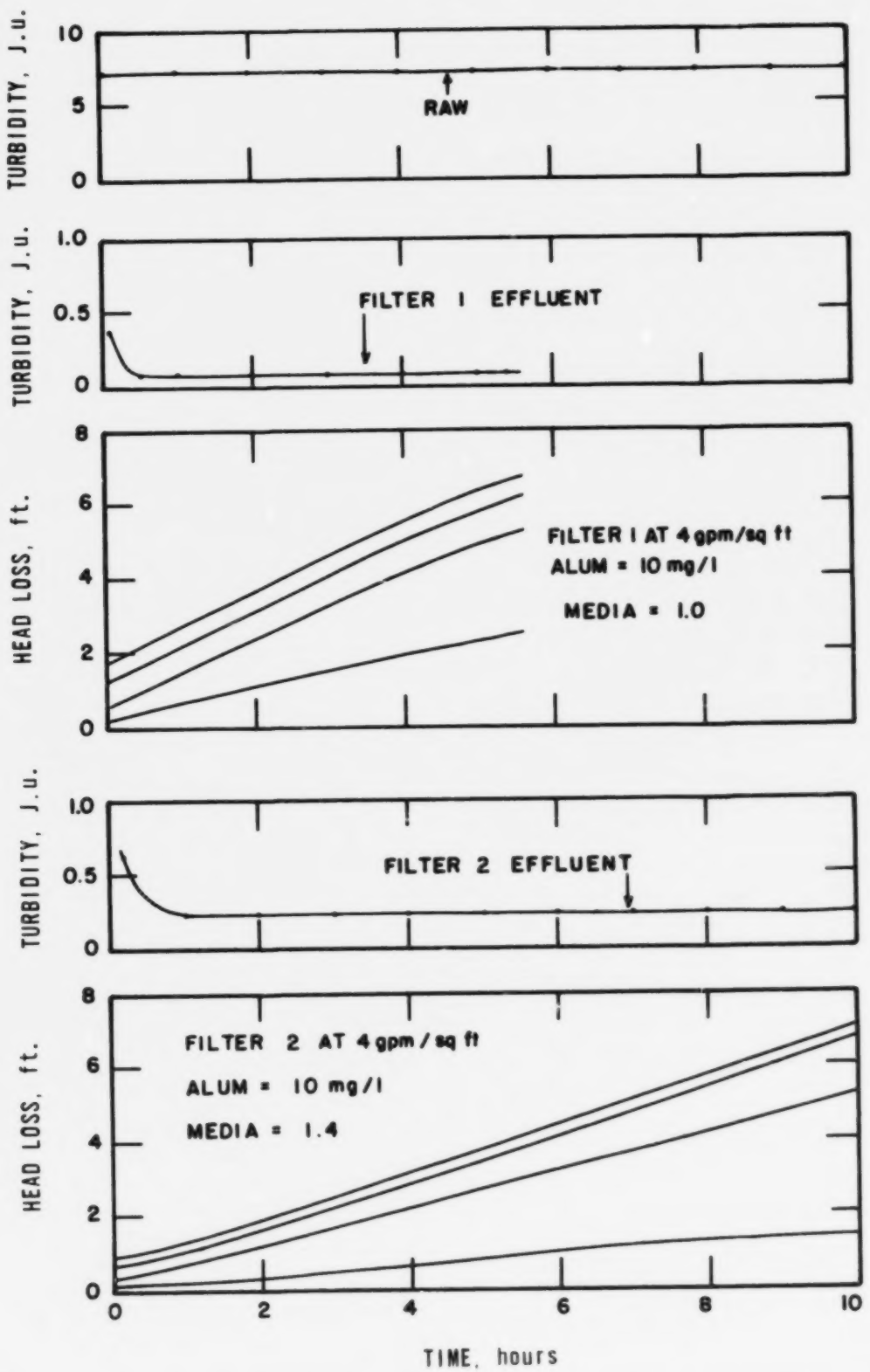

Figure 31. Head loss and turbidity values for run 5 of winter series. Feb. 15, 1965.

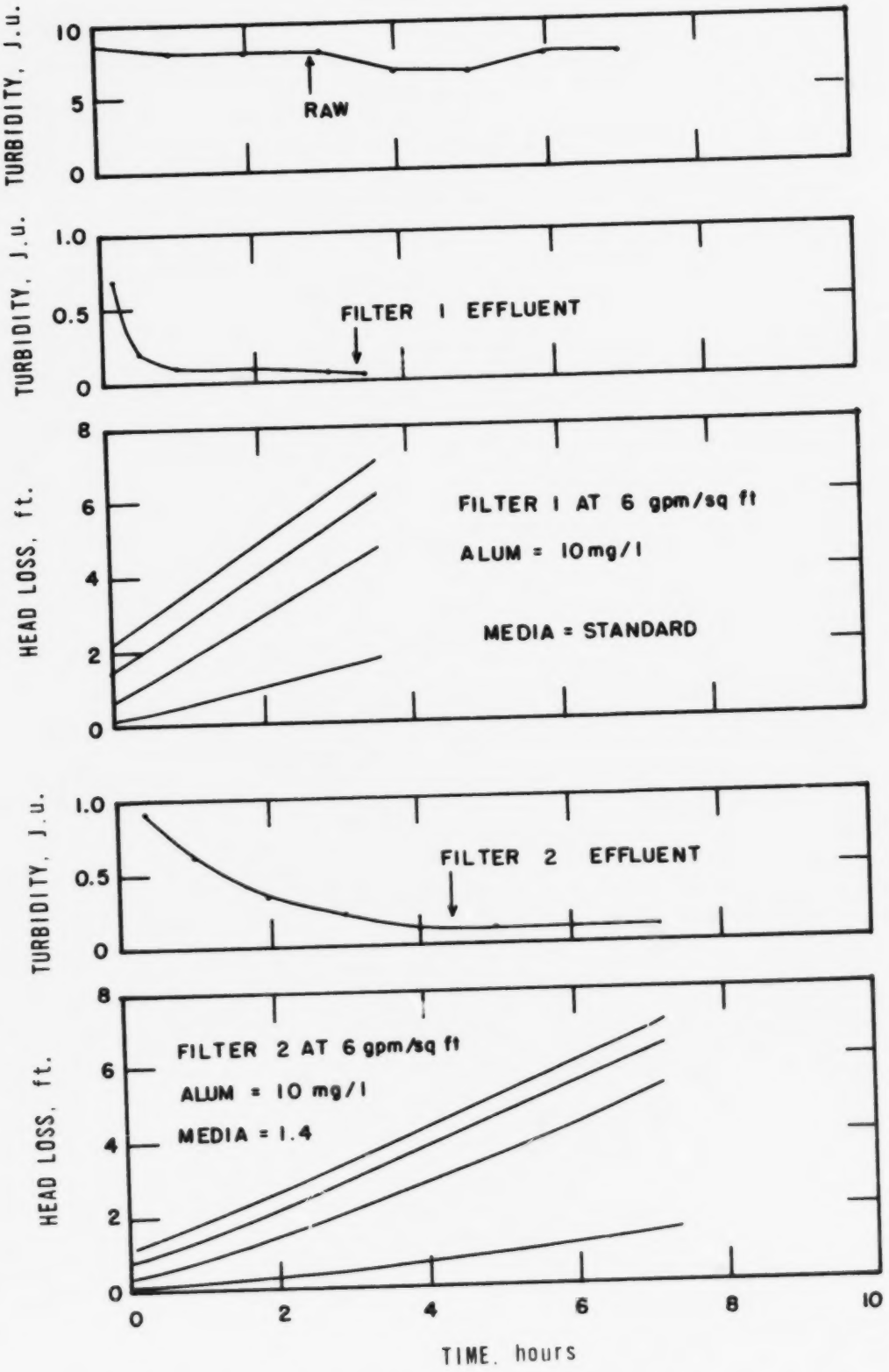

Figure 32. Head loss and turbidity values for run 6 of winter series. Feb. 16, 1965.

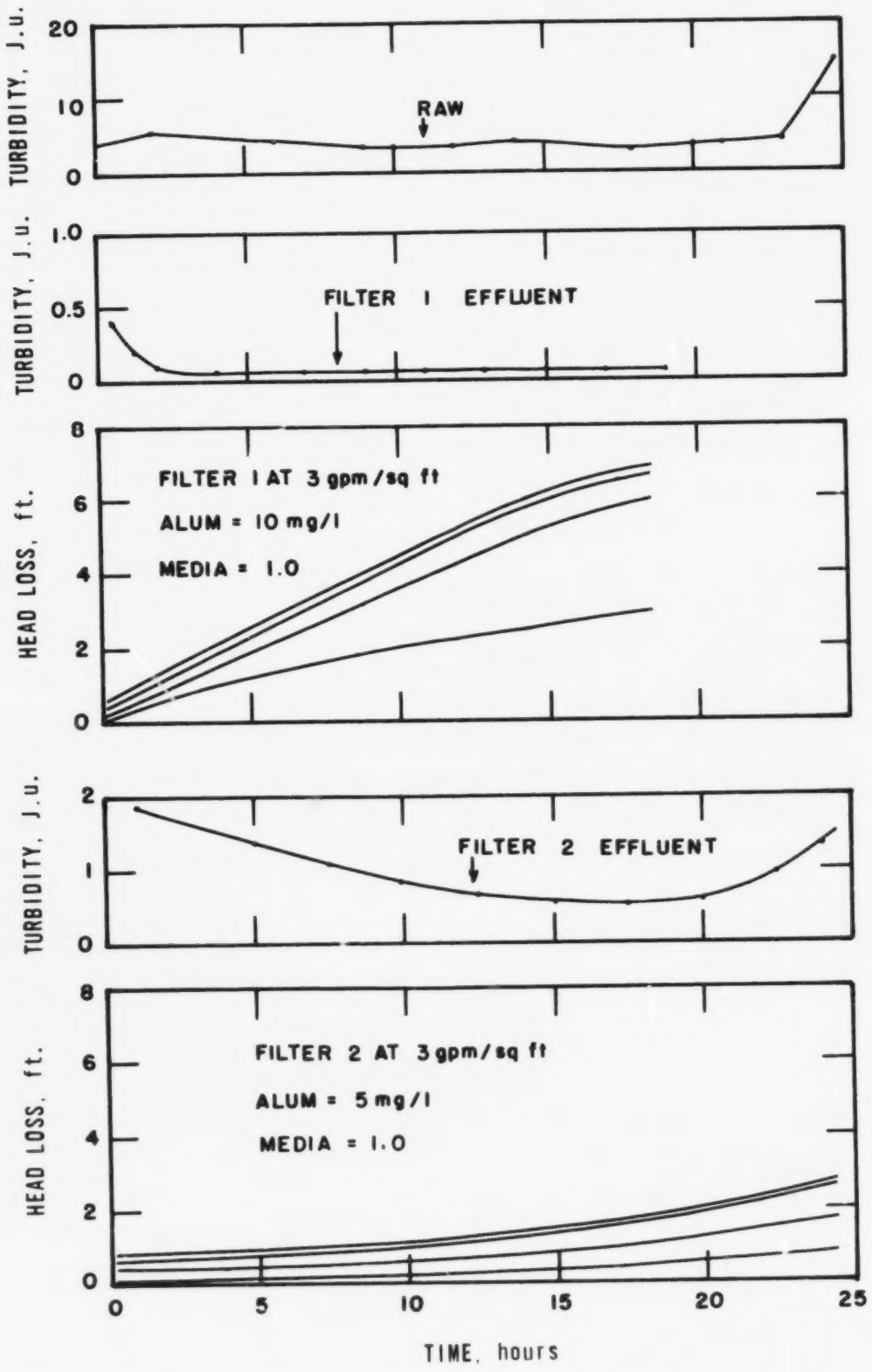

Figure 33. Head loss and turbidity values for run 1 of spring series, May 18, 1965.

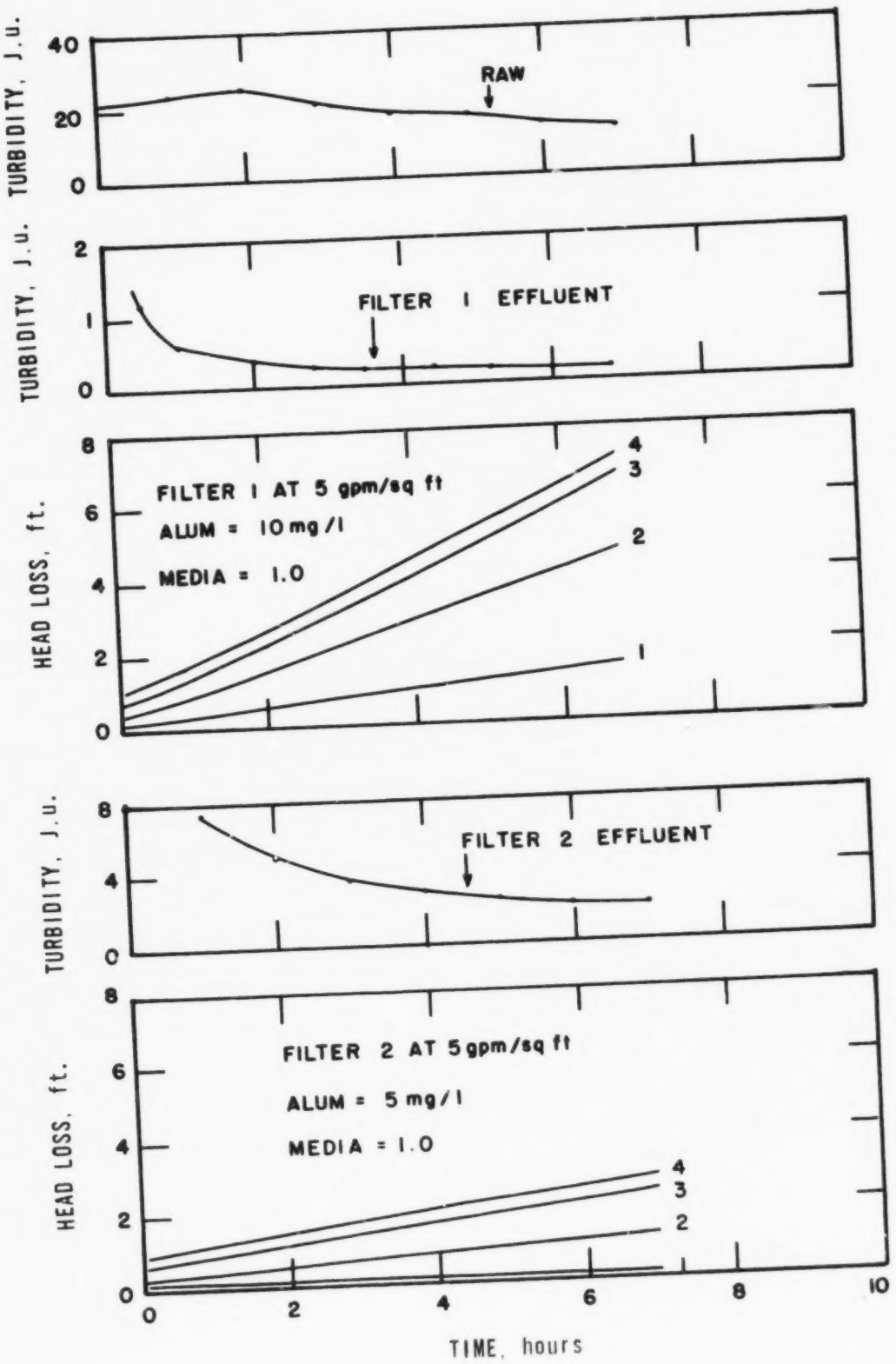

Figure 34. Head loss and turbidity values for run 2 of spring series. May 19, 1965.

After changing the alum doses to 7.5 mg/liter in filter 1 and to 12.5 in filter 2, run 3 (Figure 35) was started at a rate of 3 gpm/ft^2. Filter 1 effluent averaged about 0.4 J.u. and filter 2 about 0.2 J.u. of turbidity in the effluent. After 18 hours, filter 2 had a total head loss of 7 feet, but filter 1 continued another 6 hours before it reached a 7-foot head loss. As shown by the incremental head losses, the additional alum tended to strengthen the floc and retain it higher in the filter bed. Filter 2, upon termination, had a head loss of 5.4 feet across the coal layer, whereas filter 1 had a head loss of 3.9 feet across the coal layer, with more of the material penetrating into the sand layer.

Run 4, shown in Figure 36, was conducted at a 5-gpm/ft^2 flow rate with the same alum doses as those in run 3. Effluent turbidity from filter 1 averaged about 0.5 J.u. and from filter 2 about 0.1 J.u. Filter 2 with the higher alum dose reached a 6.8-foot head loss in 6.5 hours, and filter 1 lasted 3 hours longer to the same head loss. Comparing the incremental head losses of run 4 with run 3 shows that the increase in filtration rate had very little influence on floc penetration. Even though the higher alum dose appeared to strengthen the floc and improve the head-loss distribution, the length of run was shortened because of the added solids to be filtered out.

After the media in filter 2 was changed to coal greater than 1.4 mm, run 5 (Figure 37) was started at a filtration rate of 5 gpm/ft^2 and an alum dose of 12.5 mg/liter. Although filter 1 produced a slightly better effluent, the run length was only 6 hours as compared to 9.5 hours for filter 2 with the larger coal. Although both filters appear to have relatively unfirom distribution of head loss, more head-loss taps between the 6- and 18-inch taps (numbers 1 and 2)

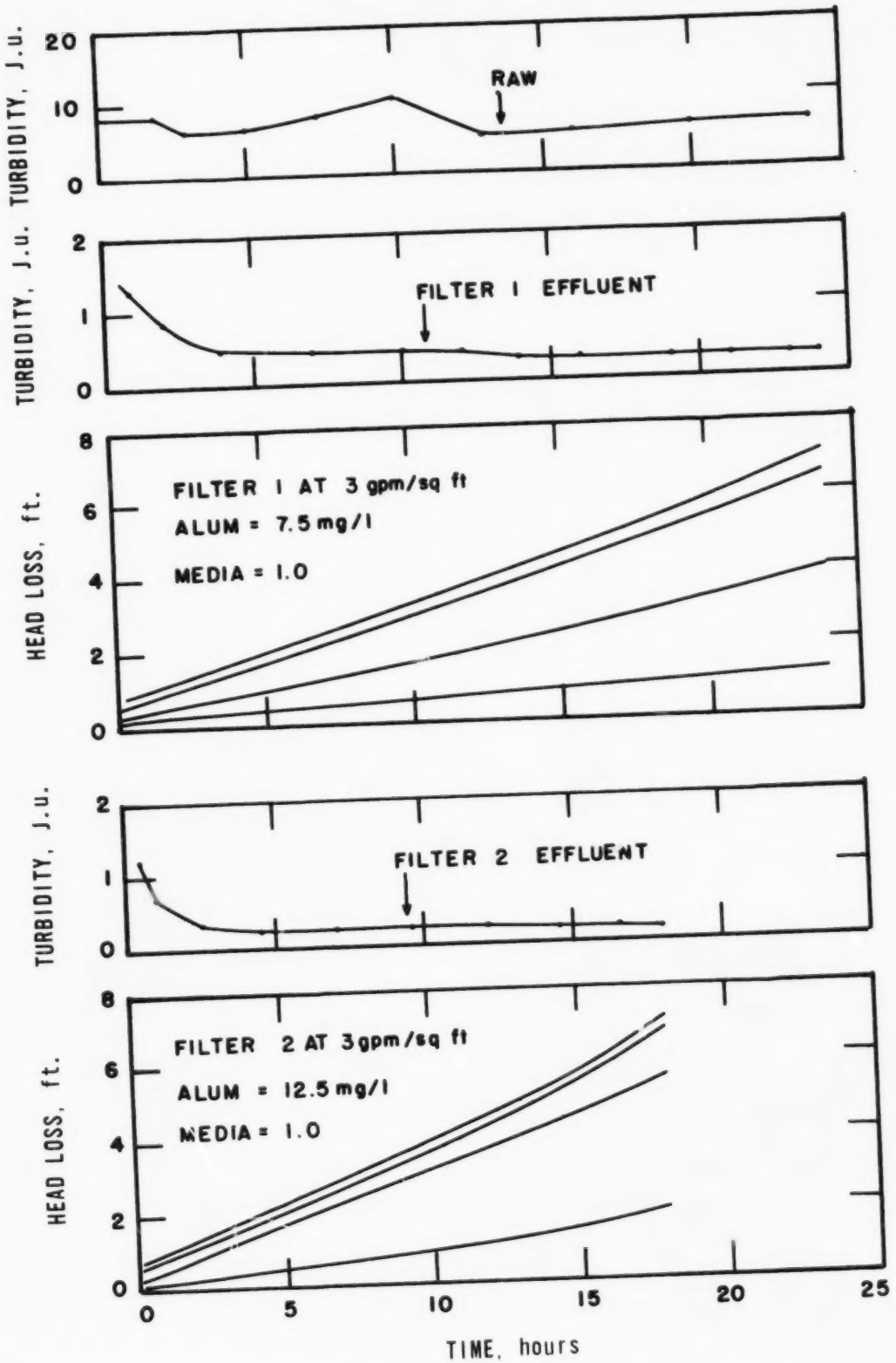

Figure 35. Head loss and turbidity values for run 3 of spring series, May 20, 1965.

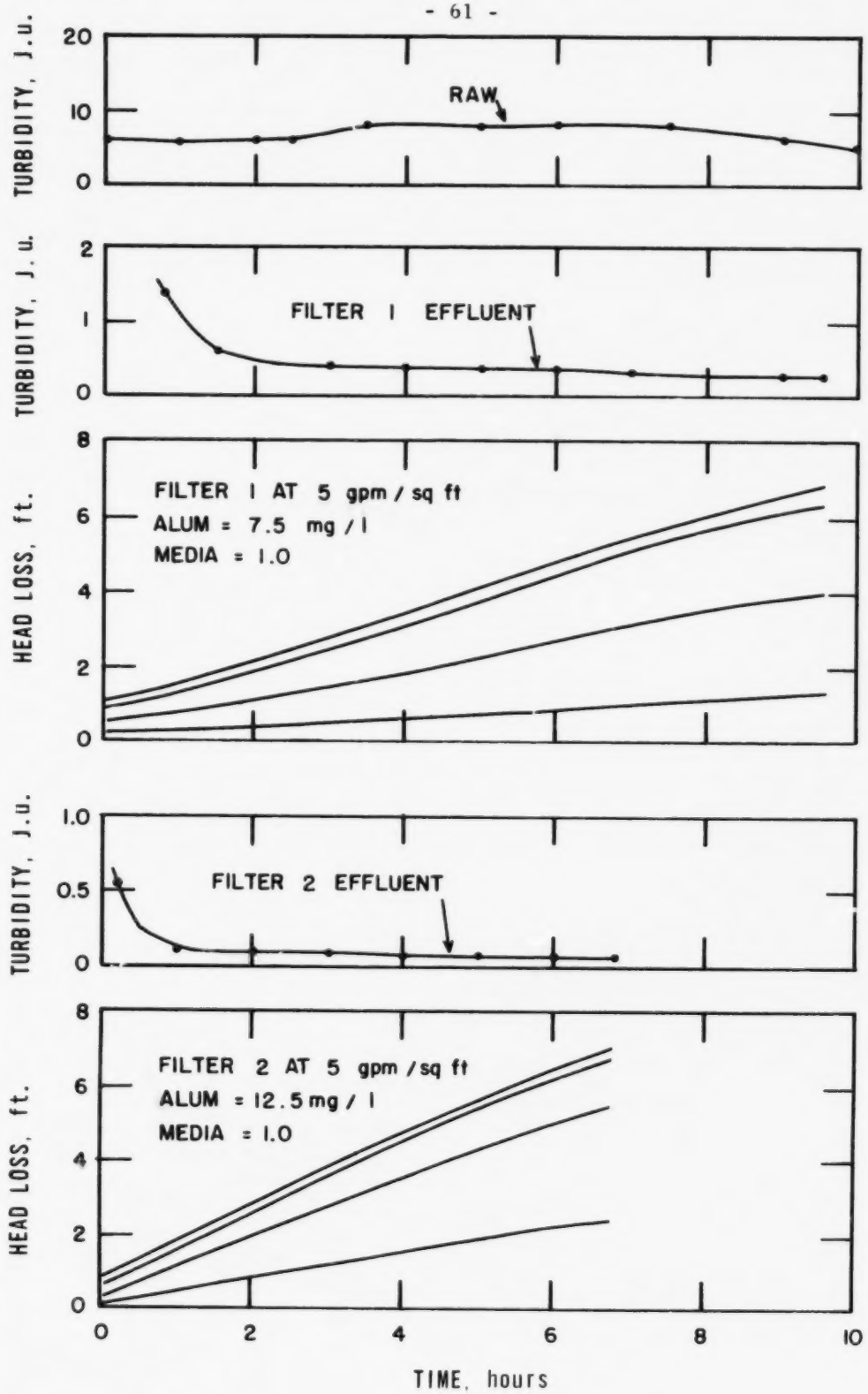

Figure 36. Head loss and turbidity values for run 4 of spring series, May 21, 1965.

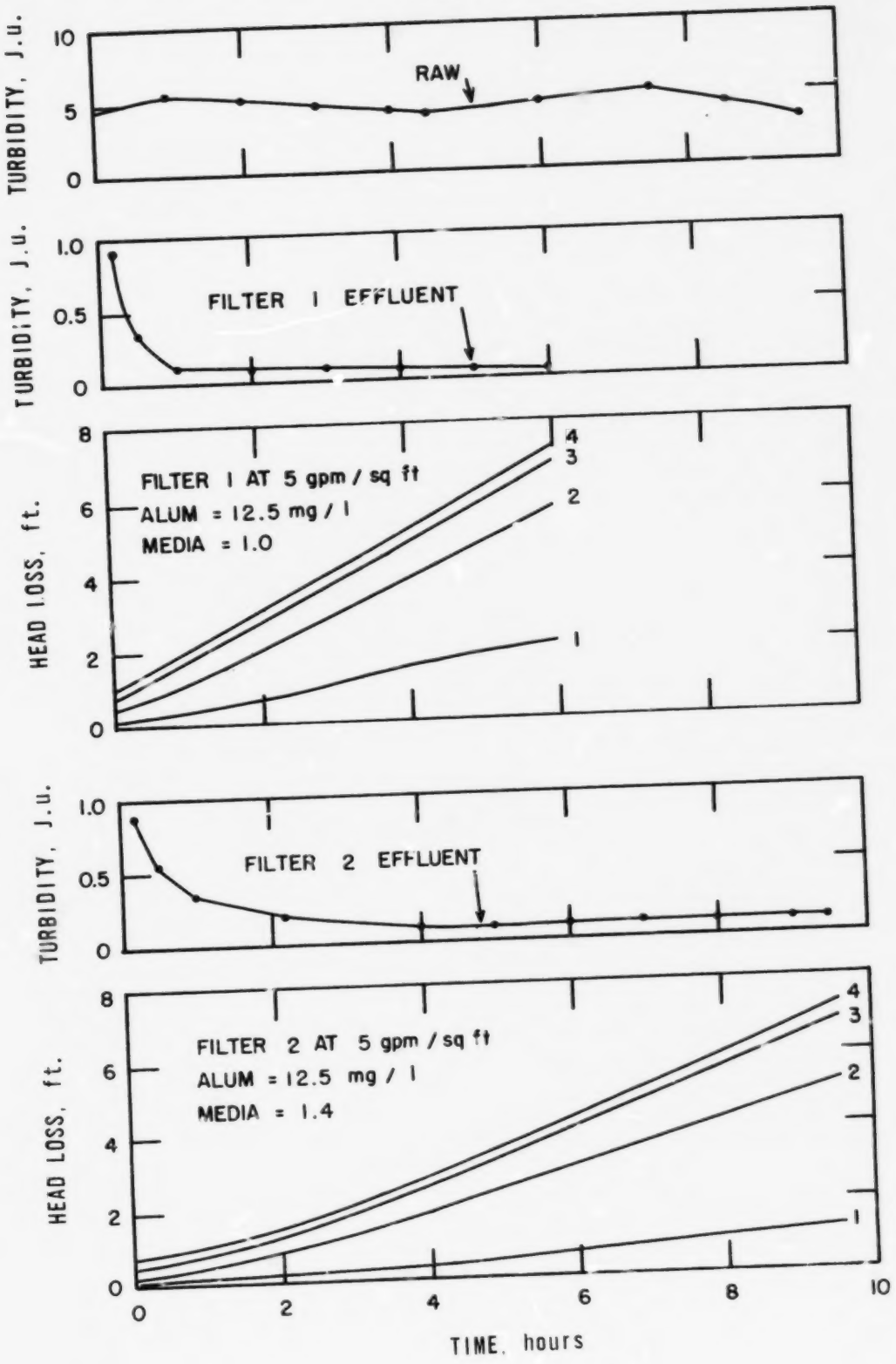

Figure 37. Head loss and turbidity values for run 5 of spring series, May 22, 1965.

might have revealed a more uniform distribution in filter 2 than filter 1. This could be explained by the larger zone for filter 2 in which the sand and coal are mixed because of the larger average size of coal used in filter 2.

Following a reduction in both the alum dose and the filtration rate, run 6 was conducted. As shown in Figure 38, the effluent turbidity from both filters increased somewhat over run 5. Although the filtration rate was reduced by two-fifths from run 6 to run 5, the length of run for both of the filters was increased by a factor of 4, with filter 2 again lasting much longer than filter 1. The lower alum dose caused a deeper penetration of floc as shown by the larger headloss increments between taps 2 and 3 for run 6 as compared to run 5.

Run 7 (Figure 39) at 5 gpm/ft^2 and 7.5 mg/liter of alum produced effluents similar to run 5 at 5 gpm/ft^2 and 12.5 mg/liter of alum. Both filters operated longer in run 7 than in run 5, probably because of the lower alum dose in run 7, even though the raw water turbidity was slightly higher in run 5. This was true in spite of a better head-loss distribution in run 5.

Increasing the alum to 12.5 mg/liter and reducing the filtration rate to 3 gpm/ft^2 improved on the effluent quality, especially in the first part of the run as shown in Figure 40 for run 8. The increased alum dose, although it improved both the effluent turbidity somewhat and the head loss distribution, markedly reduced the length of run. This is seen again by comparing run 6 and run 8. Five mg/liter

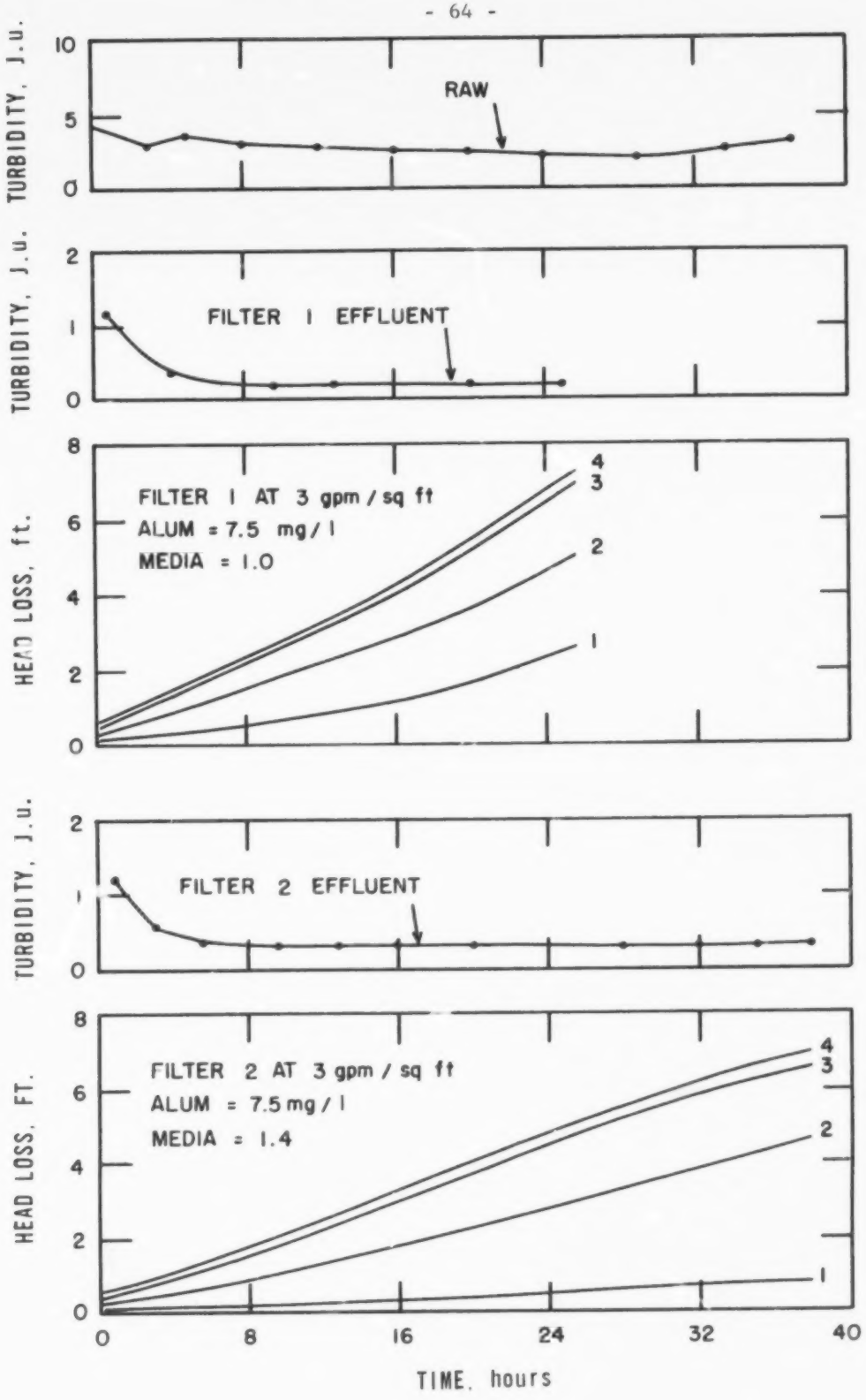

Figure 38. Head loss and turbidity values for run 6 of spring series, May 23, 1965.

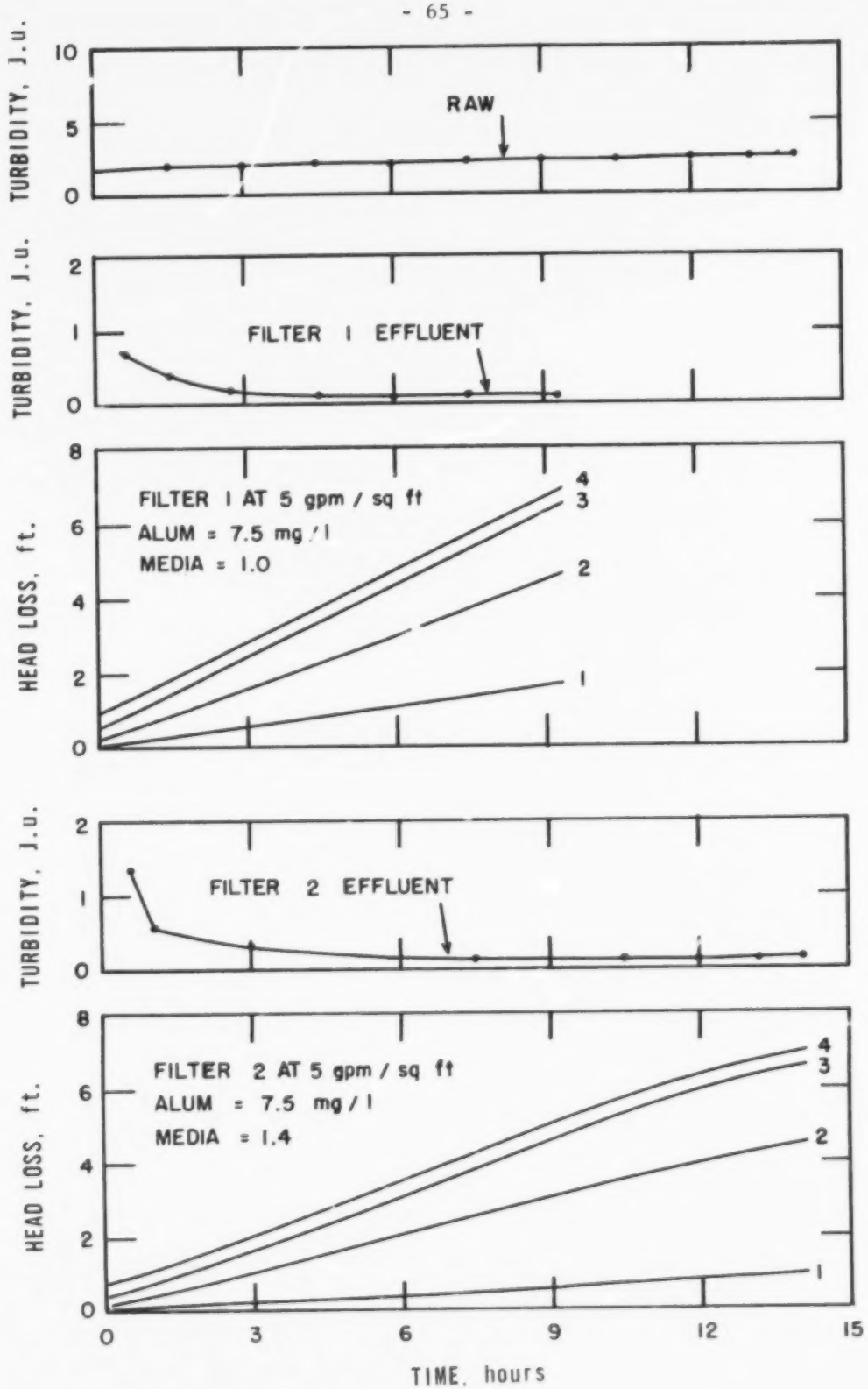

Figure 39. Head loss and turbidity values for run 7 of spring series, May 25, 1965.

of additional alum shortened the run by about 40 percent because of the added solids that had to be removed.

Algae

During many of the runs in the summer and fall series, influent and filter 1 effluent grab samples were taken for algae enumeration. Influent and effluent samples from both filters were taken once each run in the winter and spring series. All of the above-mentioned samples were taken at about the midpoint in the run and counted on site very shortly thereafter. Algae were counted by the numerical or clump count method, in which colonies and other associations of cells were counted as units, the same as isolated cells. For each sample three separate microscopic fields were examined. Because of the size of the microscopic field the algae content per ml was obtained by multiplying the average count by a factor of 31 or 27, depending on the microscope used.

A summary of the data is shown in Table 5. The algae content of the raw water varied from a low of 31 per ml found in run 1 of the winter series to a high of 960 per ml found in run 6 of the fall series. All of the effluent values reported for the winter and spring series were less than 31 algae per ml. Five effluent samples during the fall series contained some algae. The highest effluent count, resulting in a value of 100 algae per ml was found during run 6 in the fall series. This may have been a result of a marginal alum dose, 10 mg/liter, for the high turbidities encountered in the raw water.

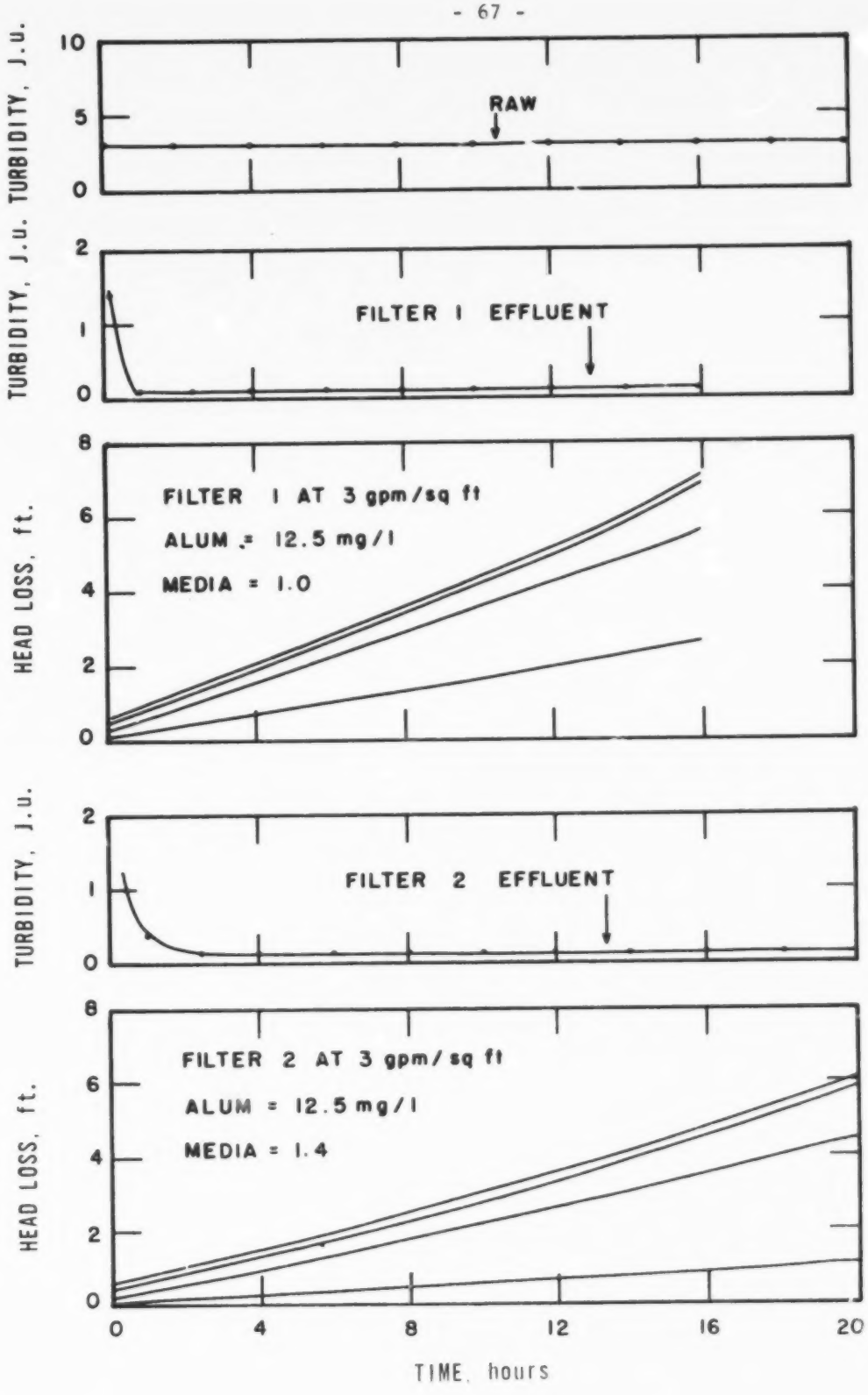

Figure 40. Headloss and turbidity values for run 8 of spring series, May 26, 1965.

Table 5. SUMMARY OF ALGAE DATA

Run No.	Algae/ml Raw	Filter-1 Effluent	Filter-2 Effluent	Run No.	Algae/ml Raw	Filter-1 Effluent	Filter-2 Effluent
		Summer series				Winter series	
5	835	< 31	-	1	31	< 31	< 31
6	465	< 31	-	2	186	< 31	< 31
7	775	-	-	3	186	< 31	< 31
8	434	-	-	4	217	< 31	< 31
				5	217	< 31	< 31
				6	217	< 31	< 31
		Fall series				Spring series	
2	217	< 31	-	1	135	< 27	< 27
3	310	< 31	1	2	135	< 27	< 27
4	310	55	-	3	108	< 27	< 27
5	434	31	-	4	135	< 27	< 27
6	961	102	-	5	189	< 27	< 27
7	558	< 31	-	6	135	< 27	< 27
8	434	31	-	7	81	< 27	< 27
9	838	53	-	8	81	< 27	< 27

The limited number of algae analyses revealed no differences in removal due to filtration rate, alum dose, media size, or combinations thereof. As with filtration rate, any influence of algae content on the length of filter run was probably masked by variations in alum dose and media size.

Production

To sort out the influence of some of the parameters on the length of run, a production number was calculated for each of the runs. This number was obtained by multiplying the filtration rate by the length of run and then dividing this product by the total head loss when the run was terminated. The values obtained are in gallons per square foot of surface area per foot of final head loss. As the value decreases for any set of conditions, the length of run is shorter and backwashing becomes more frequent and costs associated with backwashing increase.

Table 6 summarizes this information for the runs in which the standard filter was used along with 10 mg of alum per liter:

Table 6. INFLUENCE OF FILTRATION RATE ON WATER PRODUCTION

Rate, gpm/ft^2	No. of Runs	Average production	
		$gal/ft^2/ft$	gpd/ft^2 [a]
2	8	342	2,810
4	9	258	5,400
6	8	246	7,820

a - Based on an average terminal head loss of 7 ft and 30 min. down time during each backwash.

As shown, the production per foot of final head loss decreases with increasing rate. This is probably a result of the higher initial head losses at the higher filtration rates coupled with the inability of the flow at higher rates to pull the floc deeper into the filter with this filter media. Although the production per foot of head loss decreased, the production per day per square foot increased from 2,810 gallons at the 2-gpm rate to 7,820 gallons at the 6-gpm rate. The percent of water used for backwash should be similar for all three rates, but labor costs associated with backwashing would increase at the higher rates inasmuch as backwashing is more frequent. All of the above runs produced an effluent with an average turbidity below 0.5 J.u.

The next comparison was the production from parallel operation of the standard filter and the other filter containing the commercial media (Table 7).

Table 7. INFLUENCE OF FILTER MEDIA ON WATER PRODUCTION

Pairs of Parallel Runs	Average production - gal/ft^2/ft				
	Filter Media				
	Std.	1.0	1.2	1 4	1.7
4	264	408 (55)			
3	216		318 (47)		
5	240			402 (68)	
3	282				536 (85)

a - ( ) Percent increase over standard filter.

As expected, the production number increases with increasing size of coal. Table 7 is based on the fall and winter series runs since only the standard filter was used in the summer series, but the standard filter was not used at all in the spring series.

To show the influence of alum dose on the production at filtration rates of 3 and 5 gpm/ft^2, the Table 8 was developed.

Table 8. INFLUENCE OF ALUM DOSE ON WATER PRODUCTION

Rate, gpm/ft^2	Production, gal/ft^2/ft			
	Alum Dose, mg/liter			
	5	7.5	10	12.5
3	1570	618	480	462
5	750	426	288	294

Each of the eight numbers represents one of the individual filter runs during the first four runs of the spring series. Since they are not averages of several runs, less weight should be attached to any specific value; but they do show a marked trend. As with the standard filter, higher filtration rates result in lower production. The main point to be mentioned here is the importance of selecting the alum dose necessary to give the desired effluent quality. Both filter runs with a 5-mg/liter alum dose produced an effluent with an average turbidity in excess of 0.5 J.u., whereas the other three doses all resulted in an average effluent turbidity below 0.5 J.u. Alum doses higher than required to achieve the desired effluent quality markedly reduced the length of run.

The production numbers calculated for the last four runs of the spring series are shown in Table 9.

Table 9. UNIT WATER PRODUCTION FOR RUNS 5-8 OF SPRING SERIES

Rate, gpm/ft^2	Coal size	Production, gal/ft^2/ft Alum dose, mg/liter 7.5	12.5
3	1.0	630	360
3	1.4	978	588
5	1.0	396	252
5	1.4	606	402

Again, each number is the result of only one filter run. The trends mentioned previously are further confirmed with these data. Lower filtration rate, lower alum dose, and larger coal size all tend to increase the production.

Throughout the 1-year study the production values for runs in which the average effluent turbidity was 0.5 J.u. or less ranged from 150 to 980. The value of 150 was from a standard filter operated at 6 gpm/ft^2, and the upper value was obtained for filter 2, run 6 of the spring series. For the filter runs in which the commercial media combinations were used, nearly all the calculated production values fell in the 300 to 900 range. A total of 17 runs was made using the filter with coal greater than 1.0 mm. Fifteen of these runs produced an effluent with an average effluent turbidity below 0.5 J.u., and the average production number for these runs was 408. Just considering the runs at filtration rates from 2 through 4 gpm/ft^2 (nine runs), the average was 474. Nine runs were conducted with

the coal media larger than 1.4 mm, and the average production was 510 gal/ft^2/ft. At rates from 2 through 4 the average (5 runs) was 576. Alum doses were higher than necessary in several of the runs with the greater than 1.0-mm coal and 1.4-mm coal; thus, the expected production with proper alum doses would average higher than reported above. To show what this means in terms of run length, the Table 10 was derived. A final head loss of 8 feet was assumed.

Table 10. EXPECTED LENGTH OF RUN FOR VARIOUS ASSUMED PRODUCTION VALUES

Rate, gpm/ft^2	Expected length of run, hours		
	Assumed production, gal/ft^2/ft		
	300	600	900
2	20	40	60
4	10	20	30
6	7	13	20

With an expected production value of 600, the average length of run would be 40 hours at a 2-gpm/ft^2 filtration rate and 20 hours at a 4-gpm/ft^2 rate.

DISCUSSION

During this 1-year study 61 filter runs were made without the use of flocculators and sedimentation basins. Raw water conditions encountered during the four seasons were representative of those encountered by the water plant during the 12-month period. Various combinations of filter media, alum doses, and filtration rates were tested to check their influence on the finished water quality and length of run. For this study, finished water quality was determined by the continuous measurement of turbidity and the periodic checking of grab samples for pH, alkalinity, hardness, and algae populations. No attempt was made to measure coliform organisms in the effluent because of their low numbers in the raw water and previously published work,[4,5] which showed a good correlation between removal of turbidity and removal of coliform organisms, viruses, etc.

Of the 61 filter runs, 56 produced an effluent with an average turbidity of less than 0.5 J.u. Three of the five runs with effluent turbidities greater than 0.5 J.u. were purposely dosed with a low or marginal amount of alum. One of the runs had a breakthrough before a 7-foot head loss was reached, and the fifth run had no alum feed during the first 2 hours of the run because of pump trouble.

Although no attempt was made to follow the full-scale filters continuously, periodic comparisons of the effluents from the small filters with the effluent turbidity from the full-scale filter disclosed that the small filters were producing a water as good or better than the full-scale filter. This was expected since the experimental filters were being fed an equal or higher alum dose than was being used by the plant. No comparisons in length of run between the small and large filters could be made since the large filters were backwashed routinely on a time cycle since the head-loss gages did not work.

There is a noticeable difference in the effluent turbidity in the initial part of the runs of the summer and fall series compared to the winter and spring series. In the latter runs the alum feed pump and the pump acting as the rate-of-flow controller were started nearly simultaneously. This resulted in poor coagulation of some of the initial raw water and higher effluent turbidities during the early part of these runs. During the summer and fall series the alum feed was started about a minute before filtration began, thus the likelihood of passing some poorly coagulated water through the filter was decreased. Generally the filters were backwashed thoroughly so that the possibility of an initial washout would be eliminated or the amount reduced.

The length of run was influenced by the alum dose, the filtration rate, and the media size. An alum dose higher than required to produce a desired effluent quality created more solids to be removed and also appeared to strengthen the floc, both of which caused shorter runs. Most of the time, increasing the filtration rate accomplished very little increase in the distribution of removal in the filter bed. Usually any such benefit was more than offset by the increased head loss upon startup. In other words, as the filtration rate was increased, the quantity of water produced per unit of surface area per foot of final head loss decreased. This does not mean, however, that the 2-gpm/ft^2 filtration rate is the best since the total annual costs may be lower at higher filtration rates as a result of decreased capital costs.

Although no runs were made using a small amount of filter aid, based on previous work,[4,5] some of the runs could have been lengthened by the use of an aid. Upon termination of several runs, the upper part of the sand layer (between taps 2 and 3) had over 2 feet of head loss. A small amount of filter aid would have strengthened the floc and allowed more removal in the upper 18 inches of the bed and, thus, produced a longer run.

Alterations in the coal size used in the dual-media filter had a marked influence upon the length of run. Although no comparisons were made between a sand filter and any of the dual-media combinations, previous work[2] showed that the run length for the standard filter was about three times that of a sand filter operated in parallel. This study gave run lengths for the filter containing commercially available media of 45 to 70 percent longer than the run lengths of the standard

filter operated in parallel. The difference in run lengths between the standard filter and the filter containing the commercial material was a result of several factors. As the coal size at the top of the filter was increased, the size of the pores also increased, which allowed a deeper penetration of floc into the filter bed. Table 2 shows that the uniformity coefficient decreased as the coal size increased. The lowering of the uniformity coefficient resulted in a more uniform sized coal and a larger zone in which the sand and coal were mixed, both of which allowed a more efficient use of the filter bed for storage of floc.

When the coal size used in the dual-media filter was greater than 1.7 mm, a considerable amount of the removal took place in the lower half of the filter. If more runs had been made with this size coal, breakthroughs would have been expected more frequently. In fact, this is why additional runs with the greater than 1.7-mm coal were not made during the winter and spring series.

Cold water encountered during the winter season appeared to influence the distribution of floc removal. Similar runs in the summer series, except for raw water temperature, removed the floc higher in the filter media than the corresponding runs during the winter series. No other comparisons could be made because of differences in raw water turbidity, filtration rate, or media size.

Algae data obtained during this study, although limited in quantity, did not reveal any significant problems associated with their removal. Thirty to 960 algae per ml were relatively easy to remove with the various dual-media combinations tried. Any influence of algae content on length of run could not be demonstrated because of the overriding influence of filtration rate and alum dose.

Based on this 1-year study, treatment of Lake Erie water using 5 to 15 mg/liter of alum and dual-media filters will produce a high-quality water. A filter with a coal size greater than either 1.2 mm or 1.4 mm appears to be optimum for this water. With 18 inches of coal this size over 6 inches of sand and the proper alum dose, the expected run length would be about 40 hours at a 2-gpm/ft^2 filtration rate or about half that value at a 4-gpm/ft^2 rate. This run length could probably be increased by the use of more than 18 inches of coal, especially when the coal size is greater than 1.2 or 1.4 mm. This coal size results in a fairly uniform coal layer and a good distribution of the floc that is removed; thus, a deeper layer would give more storage space.

CONCLUSIONS

1. The addition of 5 to 15 mg/liter of alum to Lake Erie water followed by filtration through a dual-media filter consisting of 18 inches of coal over 6 inches of sand resulted in high-quality effluent, as measured by turbidity.

2. Effluent turbidity from the experimental filters was equal to or lower than the effluent turbidity from a full-scale filter.

3. The effluent quality of the dual-media filters was maintained at filtration rates ranging from 2 to 6 gpm/ft^2.

4. Size of coal used in the dual-media filter had a small influence on effluent turbidity and a large influence on length of run.

5. The optimum coal size at the surface of the dual-media filter appears to be in the range of 1.2 to 1.4 mm.

6. Alum doses in excess of that necessary for the desired effluent clarity markedly reduced the length of run.

7. Algae encountered during the test periods were easily removed and did not appear to have much influence on the lengtn of run.

ACKNOWLEDGMENTS

Staff members Gene Sommerville and James F. Kreissl performed the filter runs and recorded the data with meticulous care. Excellent cooperation was obtained from many personnel of the Bureau of Water, Erie, Pennsylvania.

REFERENCES

1. Project report. High-rate filtration study at Gaffney, South Carolina, water plant. USPHS, Robert A. Taft Sanitary Engineering Center, May 1963.

2. Project report. High-rate filtration study at Easley, South Carolina, water plant. USPHS, Robert A. Taft Sanitary Engineering Center, August 1965.

3. Project report. High-rate and dual-media filtration study in a northwestern Ohio water plant. USPHS, Robert A. Taft Sanitary Engineering Center, January 1966.

4. Robeck, G.G., N.A. Clarke, and K.A. Dostal. Effectiveness of water treatment processes in virus removal. JAWWA. 54:1275, October 1962.

5. Robeck, G.G., K.A. Dostal, and R.L. Woodward. Studies of modifications in water filtration. JAWWA, 56: 198, February 1964.